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TECHNICAL REPORT AFATL-TR-75-17

EVALUATION OF RHEOLOGICAL PROPERTIES OF FLAME FUELS USING A CAPILLARY EXTRUSION RHEOMETER

FAE AND FLAME BRANCH
MUNITIONS DIVISION

JANUARY 1975

FINAL REPORT: JANUARY 1973 TO JULY 1974

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This report describes a research effort to develop methods to study the flow properties, such as viscosity and elasticity, of polymer solutions used as flame agents. Viscosity of the polymer formulations were studied at -3.89°C ([redacted]) and 23.9°C ([redacted]) using a capillary extrusion rheometer. Several brands of gasoline were used to prepare the polymer solutions, which gave varied flow curves under increased shear stresses. The flow curves exhibited considerable variation when different brands of gasoline were used to prepare

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the polymer solutions. The capillary length and die swell methods were used to study the elastic properties of the polymer solutions.

PREFACE

This technical report is based on a study conducted at the Air Force Armament Laboratory, Armament Development and Test Center, in support of Project 10820302 during the period from January 1973 to July 1974.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

WILLIAM F. BROCKMAN, Colonel, USAF
Chief, Munitions Division

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SECTION I

INTRODUCTION

Requirements for firebombs include a capability for high speed delivery over a wide temperature range. High speed delivery conditions expose the firebomb fuel to high wind shear forces as well as the explosive forces used in dissemination of the fuel. In addition, temperature dependence of the flow behavior of a thermoplastic material such as the polystyrene in Napalm B results in large variations in its properties.

The rheological properties of concentrated polymer solutions are of major importance in the development of improved flame agents for these high speed delivery conditions over a wide temperature range. An understanding of the rheological behavior of standard agents (such as Napalm B) and candidate systems will enable researchers to predict the behavior of candidate fuels based on laboratory studies, as well as providing guidance as to the type of materials which should be investigated.

The rheological properties which are most important to fuel behavior are the viscosity and elasticity (termed recoverable shear or percent memory) as a function of shear rate. Gaskins[1] has correlated shear rate with the velocity of a gelled hydrocarbon extruded at high speeds from a nozzle. Based on these calculations, it has been estimated that exposure of a fuel to an air stream at 900 feet per second is equivalent to a shear rate in the range of 10^6 sec^{-1}.

Numerous researchers have studied the viscosity of flame agents with rotational viscometers such as the Brookfield or MacMichael instruments; however, these instruments are limited to low shear rate ranges and require exposure or the sample to the atmosphere during the measurement. Gaskins[2] has designed a capillary extrusion rheometer to study both viscosity and recoverable shear as a function of shear rate. However, the instrument utilized is limited in shear rate to about 10^5 sec^{-1} and requires numerous runs to overcome data scatter. The technique utilized for studying recoverable shear involves a large number of laboratory experiments and a long data reduction process.

Reference

1. Gaskins, Frederick. A Study of Jet-Tension Instrument and Mechanical Flame Thrower. Franklin Institute Report F-A 1978.
2. Gaskins, Frederick. Rheological Properties and Performance of Napalm B in Comparison to Standard Flame and Incendiary Agents (U). EATR 4155, February 1968.

The objective of this study was to develop simple instrumentation and reproducible techniques necessary to study the rheological properties of polymer solutions. A parallel, contractual effort [3, 4] was utilized in part to develop the required instrumentation.

To establish the procedures and provide a data baseline for comparison with experimental formulations, an extensive investigation of Napalm B has been included in this study.

Reference

3. Long, R. L. Flame Agents for High Velocity/Low Temperature Use (U). Air Force Armament Laboratory Report AFATL-TR-71-55. Monsanto Research Corporation, May 1971.

4. Long, R. L. Improved Flame Agents (U). Air Force Armament Laboratory Report AFATL-TR-72-177. Monsanto Research Corporation, September 1972.

SECTION II

THEORETICAL

Rheology is the science of the deformation and flow of matter. Comprehensive theoretical discussions of rheology are adequately discussed in the literature.[5] A limited explanation of the parameters studied and the equations used to calculate these parameters will be included.

The deformation of a body can be arbitrarily divided into two general types: (1) spontaneously reversible deformation called elasticity, and (2) irreversible deformation called flow or viscous behavior. In an idealized case, if deformation is carred out infinitely slow, there will be no viscous contribution and only elastic effects will show up. On the other hand, in continuous, steady-state flow at a uniform rate there will be no elastic contribution and the entire effect will be viscous.

The polymer solutions studied in this program exhibit both reversible deformation or elasticity and irreversible deformation or flow and are called viscoelastic materials.

SHEAR STRESS

To produce flow or an elastic strain, a stress, defined as a force per unit area, must be applied. In a capillary extrusion rheometer, it is assumed that steady flow is obtained in the capillary and that all the forces applied to the solution cause flow. In this case, the viscous forces tending to retard the flow will be exactly balanced by the force resulting from the pressure differential between the two ends of the capillary. The shear stress in a fluid flowing through a capillary is directly proportional to the distance from the center of the capillary, varying from zero shear stress at the center to a maximum at the wall. The most convenient location for measurement of the shear stress is at the wall of the capillary. The shear stress applied at the wall in the capillary extrusion rheometer used in this study is calculated from the following equation:

$$T = \frac{Fr}{2\,R^2L}$$

Reference

5. Van Wazer, J. R., et. al. <u>Viscosity and Flow Measurement.</u> Interscience Publishers, 1963.

where: T = Shear stress, dynes/cm^2

F = Force applied (ram load, dynes)

r = Orifice radius, cm

R = Barrel radius, cm

L = Orifice length, cm

SHEAR RATE

The rate of deformation for flow is a function of shear. Simple shear can be considered as a process in which infinitely thin, parallel plates slide over each other.

Viscous deformation is expressed in terms of rate of shear, which is the change in velocity of flow with a distance measured at right angles to the direction of flow. In the capillary rheometer, the rate of shear also varies with the radius of the capillary and must be calculated at the same point as the shear stress for the construction of flow curves. The shear rate at the wall is a more difficult quantity to determine from experimental data than shear stress. For the calculation of shear rate at the wall in a capillary extrusion rheometer, the Rabinowitsch[6] correction factor is applied to the rate of shear which has been calculated from the volumetric flow rate of the fluid, according to the following equation:

$$\dot{\gamma}_{\dot{\omega}} = \left(\frac{4Q}{\pi r3}\right)\left(\frac{3+b}{4}\right)$$

where: $\dot{\gamma}_{\dot{\omega}}$ = Corrected shear rate, sec^{-1}

Q = Extrusion rate in cm^3/sec^{-1} = volume extruded/extrusion time

r = Orifice radius, cm

$\left(\frac{3+b}{4}\right)$ = Rabinowitsch correction factor, where b is the slope of the flow curve (log shear rate versus shear stress)

Reference
6. Rabinowitsch, B., Z. Physik, Chem., A 145, 1 (1929).

VISCOSITY

The ratio of applied shearing stress to rate of shear for ideal viscous bodies is called the coefficient of viscosity or, more commonly, viscosity. This viscosity is a measure of the resistance to flow and can be expressed as:

$$\text{Viscosity} = \frac{\text{Shear stress}}{\text{Shear rate}}$$

or

$$N = \frac{T}{\dot{\gamma}_{\omega}}$$

The ideal viscous body is the Newtonian fluid for which the coefficient of viscosity is a constant. If the viscosity changes with shear rate or shear stress, it is called non-Newtonian or apparent viscosity. Most solutions of polymers, such as polystyrene, exhibit an apparent viscosity that is constant at low shear rates and then decreases in magnitude as the shear rate is increased. This decrease in viscosity as the shear rate is increased is called shear thinning or pseudoplastic flow.

ELASTICITY

The calculation of shear stress, shear rate, and viscosity from the equations shown assumes that the energy input to the solution, or the pressure drop across the capillary, is primarily utilized to overcome viscous resistance to flow, and that all other effects are small and can be neglected. Since the capillary has rigid walls, the elastic deformation of the fluid is minimized. However, when the fluid emerges from the capillary, it is no longer restrained by the walls, and energy which was reversibly stored is recovered by expansion of the fluid. Thus, highly viscoelastic materials may have elastic components that reversibly absorb a portion of the energy input. Philippoff and Gaskins[7] have discussed this elastic energy correction and have developed a graphical procedure for the calculation of recoverable shear stress, based on the capillary length.

a. Recoverable Shear

In order to determine the elasticity or recoverable shear by the capillary length technique, the polymer solutions are extruded through capillary tubes of the same diameter but of different lengths. Flow curves (log shear rate versus log shear stress) are then prepared for each capillary. From these plots, the pressure differential (ΔP) required

Reference

7. Philippoff, W. and Gaskins, F. H., "The Capillary Experiment in Rheology," Transactions of the Society of Rheology, II (1958), p. 263-284.

for each capillary with a different length and radius (L/r) ratio is determined at various levels of shear rate. Figure 1 is an example of this type plot for Napalm B at 23.9°C (75°F). This procedure is required to obtain the data for each capillary over a variation of shear rates. Plots are then made of ΔP versus the L/r ratio for each selected shear rate, as in Figure 2. For each of the shear rates plotted, there is an initial pressure drop (ΔP) at L/D = 0 which is a combination of the entrance losses and the pressure input that is reversibly stored and can be recovered outside the capillary. Flow curves of data collected with various capillaries give a curve independent of capillary dimensions, indicating that the end effects are negligible; thus, the initial pressure drop is primarily the pressure input that is reversibly stored and can be recovered outside the capillary. Philippoff and Gaskins[7] have shown that the most direct way of determining the elastic energy function is by measuring the x-intercept (as in Figure 2) and calculating the recoverable shear as:

$$S_r = -2 \text{ (x-intercept)}$$

The recoverable shear is then plotted against shear rate as in Figure 3.

b. Memory

Monsanto Research Corporation[5] has shown that the elasticity of a polymer solution can also be studied by measuring the expansion of the solution as it is extruded from the capillary. The basic technique for determining the die swell or memory of polymer melts is the measuring of the diameter of the extruded polymer strand. For the solutions studied in this program, the liquid strand is photographed as it emerges from the capillary and the measurements are made from the photograph. The diameter of the extruded strand, D_1, and the capillary orifice diameter, D_o, are used to calculate the percent memory by the following equation:

$$\text{Percent memory} = \frac{D_1 - D_o}{D_o} \times 100$$

From the equation it can be seen that if the extruded strand is the same diameter as the orifice, the solution has no recoverable shear and the percent memory will be zero. The percent memory is plotted as a function of the shear rate as shown in Figure 4 for Napalm B at 23.9°C (75°F).

c. Comparison of Recoverable Shear and Memory

The elastic nature of a polymer solution can be studied by either the capillary length or memory technique. In the capillary length technique, the energy which is recoverably stored in the solution is measured. While the theoretical basis of the technique is sound, a considerable number of

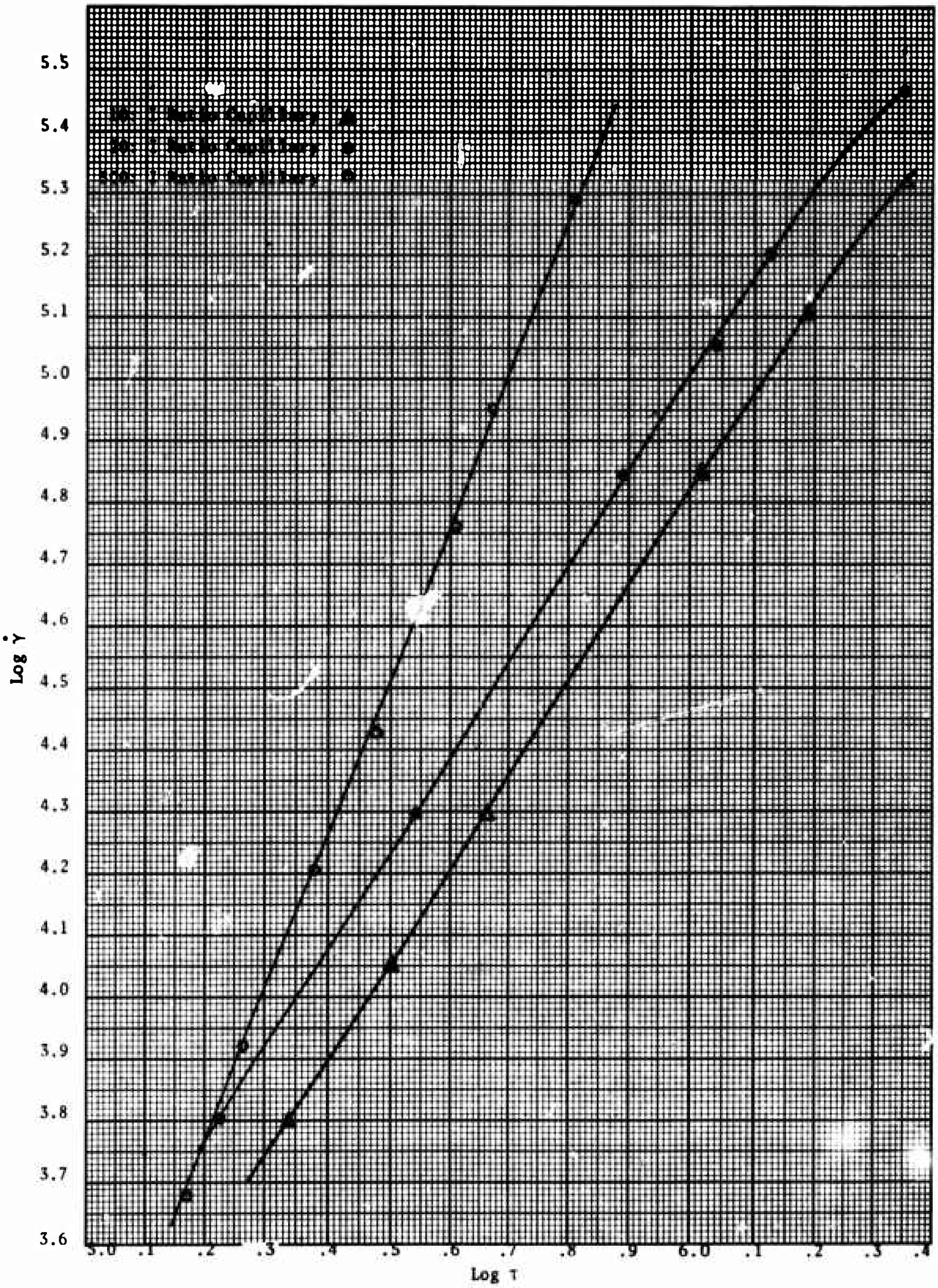

Figure 1. Log Shear Rate versus Log Shear Stress of Various Capillaries at 23.9°C

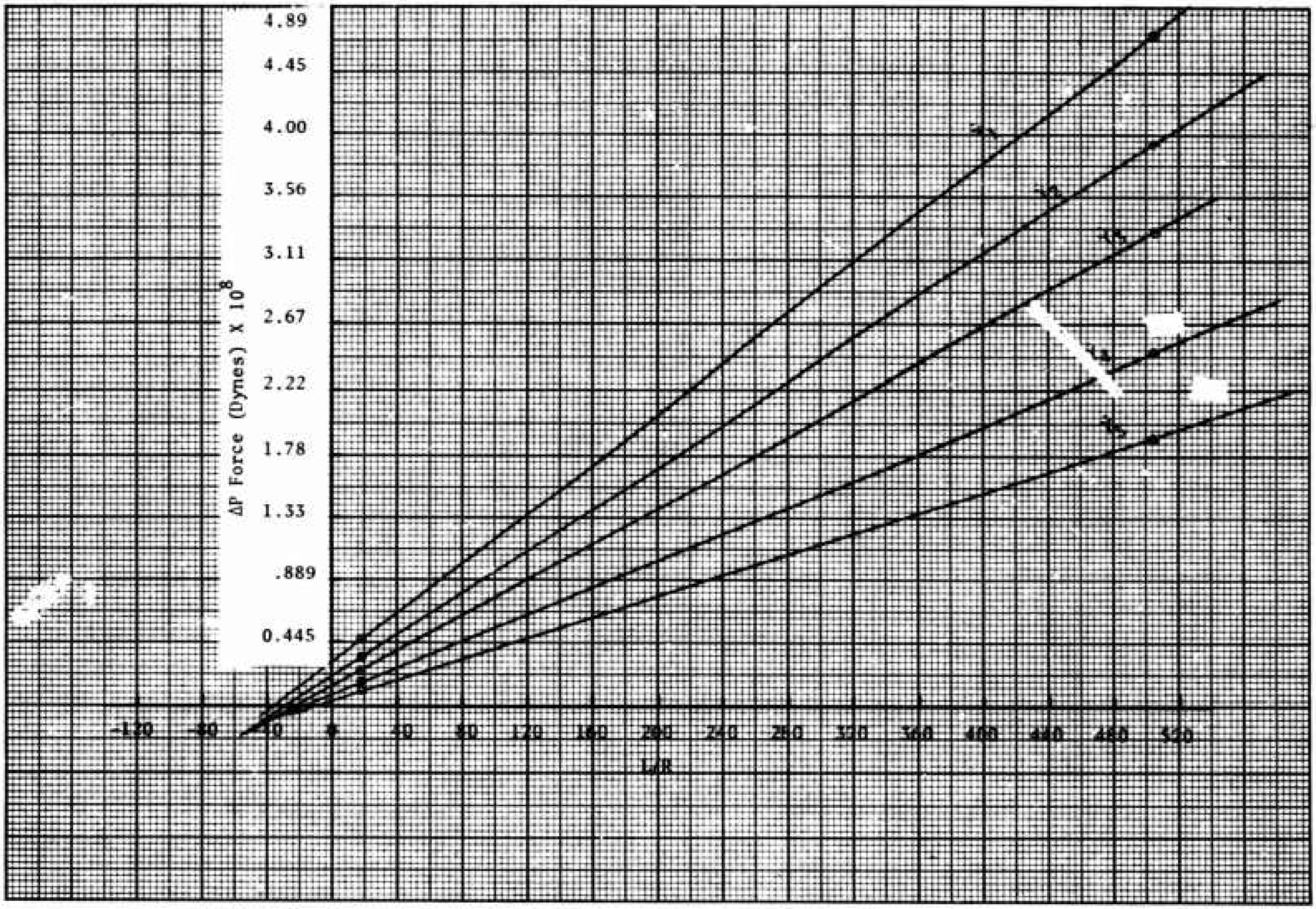

Figure 2. Pressure (Dynes) versus L/D of Two Different Size Capillaries at Four Different Shear Rates at 23.9°C

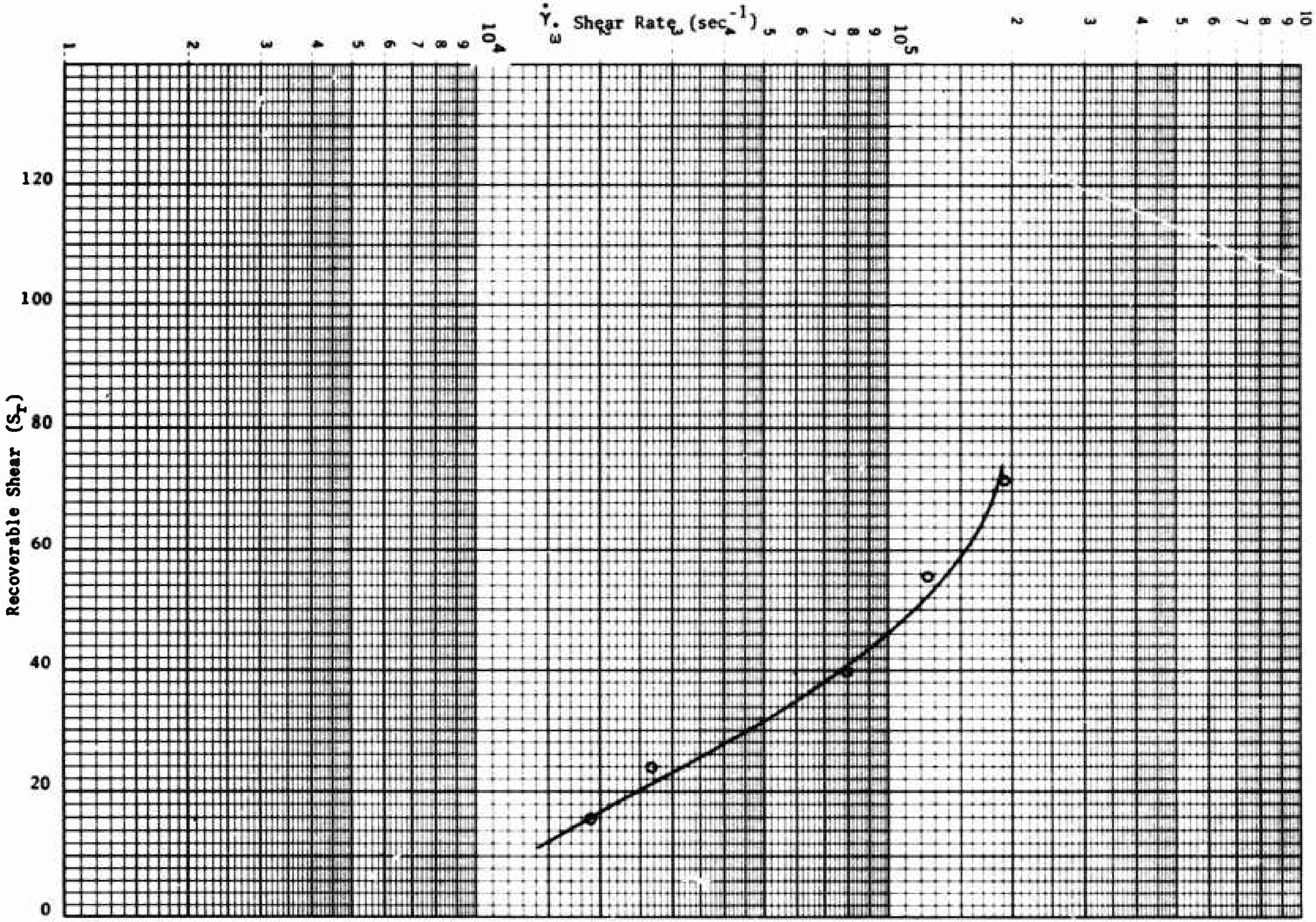

Figure 3. Recoverable Shear versus Shear Rate for Napalm B

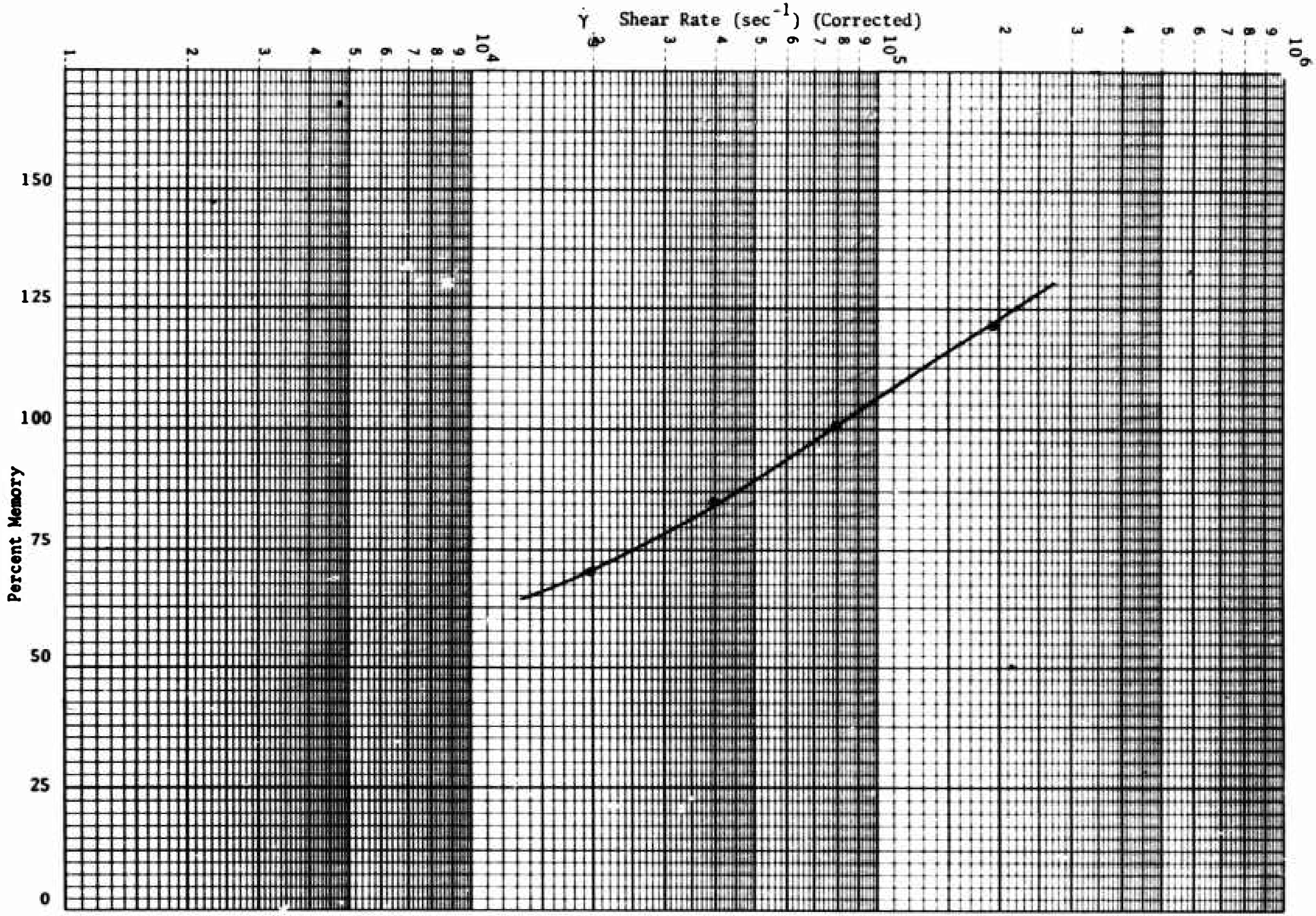

Figure 4. Percent Memory versus Shear Rate for Napalm B

measurements are required, with an involved analysis procedure to determine the recoverable shear number. In the memory technique, the physical response to the stored energy or the swelling of the material emerging from the capillary is measured. While the technique is more empirical than theoretical, the procedure required for measuring the phenomenon is considerably easier than that for determining the recoverable shear. Either of the methods can be applied to the problem of predicting the behavior of candidate flame fuel formulations on a relative basis. The relationship between recoverable shear and memory is discussed by Bagley and Duffy[8]. It is a complex relationship deeply involved with rheological theory and is beyond the scope of this report.

Reference

8. Bagley, E. B. and Duffy, H. I., "Recoverable Shear, Strain, and the Barnus Effect in Polymer Extrusions," Transactions of the Society of Rheology, 14:4 (1970), p. 545.

SECTION III

EXPERIMENTAL

APPARATUS

The flow data obtained during this study was acquired using a modified Monsanto Research Corporation Model 3501 Capillary Extrusion Rheometer shown in Figure 5. The instrument is designed for measuring the melt flow of thermoplastics. In addition to a capability for determination of the ASTM melt index, provisions are made in the design to vary the temperature from -17.8°C (0°F) to 204.4°C (400°F) and the pressure or stress applied from 0 to 160 psi. The L/r (length to radius) ratio of the capillaries used may be varied over a wide range. Thus, varying the capillaries used and the applied pressure, shear rates to 10^4 sec^{-1} can be obtained with the basic instrument. Additional modifications to the instrument by the Air Force Armament Laboratory have extended the shear rate range to 10^6 sec^{-1}.

For operation at temperatures of 40°C and below, temperature control is obtained by circulating a cooling fluid through the barrel from an external cooler. The temperature controllers and heaters built into the instrument are used to maintain the desired temperature. Measurements below -6.7°C (20°F) were not attempted because of water condensation inside the barrel.

Pressure is applied to the solution with a ram driven by oil pumped nitrogen in the range of 0 to 160 psi gauge reading. Dual gages are used to improve the precision of the measurements in the lower pressure ranges. The ram designed for the instrument is fabricated of stainless steel with a loose fit to the barrel wall. At higher pressures this loose fit allows some flow-by of material past the ram. To eliminate this flow-by, the ram has been modified by the addition of a Teflon® sleeve on the lower 12 to 15 mm of the ram. (Figure 6 shows the rams used in this study.) This sleeve is slightly tapered with the larger portion at the bottom, thus allowing the Teflon® to flow when under pressure. To compensate for the friction between the Teflon® and the wall, the instrument is calibrated with a Moorhouse Ring Dynamometer with the ram in place to determine the actual force on the solution at each pressure setting at various temperatures.

The capillary is located at the bottom of the barrel and is held in place by a retaining nut shown in Figure 7. The small rod on the nut is used as a reference for measurement of the strand diameter in the determination of elasticity as memory. The capillary length and diameter is selected according to the viscosity of the solution and the shear rates desired. The smaller diameter capillaries made in the Air Force Armament Laboratory machine shop were fabricated from constant bore, type 316 stainless capillary tubing. The capillary tubing was set into the machined capillary

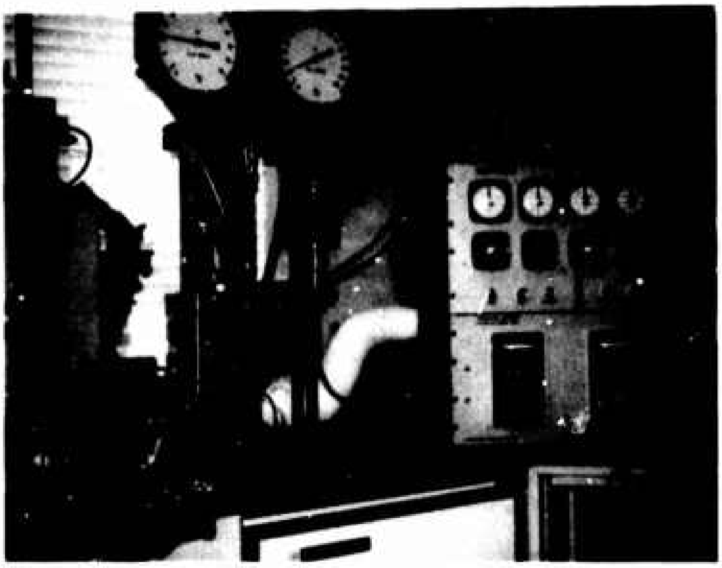

Figure 5. Capillary Extrusion Rheometer

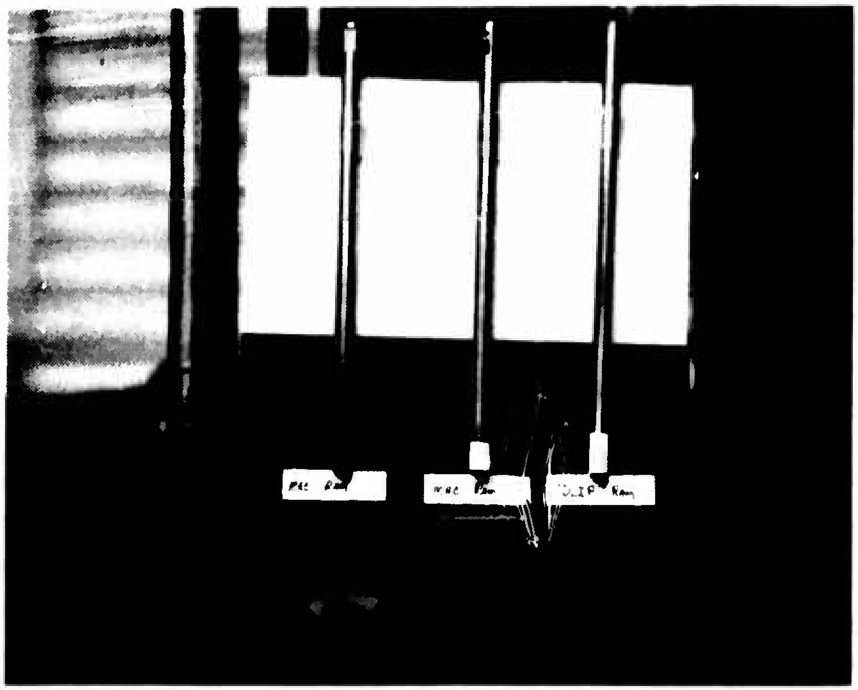

Figure 6. Extrusion Rams used in the Study

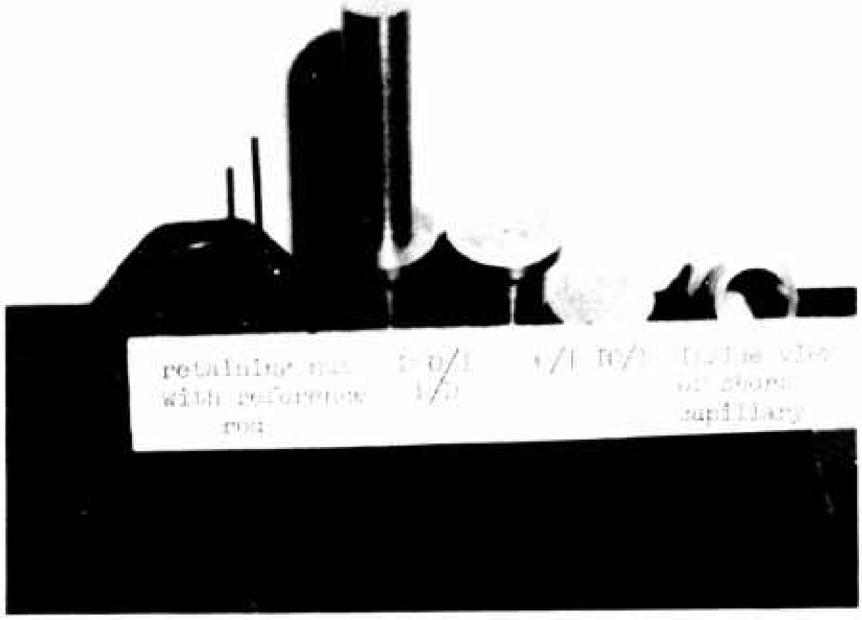

Figure 7. Capillaries used for the Recoverable Shear (S_r) Study

block by freezing the capillary tube and inserting it into the pre-drilled block, which is heated to enlarge the hole for tube insertion. Figure 7 also shows several of the capillaries fabricated by the Air Force Armament Laboratory machine shop. Table I gives a summary of the capillaries used in the study. The dimensions of each capillary used in the study were measured by physical means, using a micrometer to determine the length and an optical comparator to determine the diameter. The viscosities of Brookfield standard solutions were then determined with each capillary to verify these measurements.

The basic rheometer is equipped with four timers which are used to measure the time required to extrude a predetermined volume of material to the nearest 0.01 minute. Using a series of microswitches riding on a cam traveling with the ram, the rheometer in the automatic mode first compresses the fluid, then extrudes four set volumes of material in series from a single filling of the barrel. The time required for each extrusion of 1.245 cm^3 (0.0762 in^3) is recorded. To obtain higher shear rates or study less viscous materials where the times are very short, a Hewlett-Packard Model 5325B electrical counter (Figure 8), capable of measuring to 0.0001 second, has been wired into the first and last microswitches

TABLE I. CAPILLARY REFERENCE DATA

SOURCE	RATIO L/R	LENGTH (cm)	DIAMETER (cm)
AFATL	10/1	0.125	0.0250
AFATL	20/1	0.2525	0.0250
AFATL	49.8/1	1.2450	0.0500
MRC	65.7/1	2.5450	0.0775
AFATL	66.9/1	2.5088	0.0750
AFATL	74.9/1	1.8725	0.0500
AFATL	99/1	1.2375	0.0250
AFATL	99.8/1	2.4950	0.0500
AFATL	150/1	1.8750	0.0250
MRC	176/1	1.8608	0.0213
AFATL	200/1	2.5088	0.0250
AFATL	499.8/1	6.2475	0.0250

AFATL - Made by the Air Force Armament Laboratory

MRC - Made by the Monsanto Research Corporation on the cam. By setting the rheometer to the manual mode of operation, the entire volume of the barrel, 6.751 cm^3 (0.4119 in^3), may be extruded at one time with an accurate measure of the time required; also, the pressure is recorded during the extrusion for each data point.

For the determination of elasticity by the memory technique, the strand of polymer being extruded is photographed with a Singer Super Graphic Camera equipped with a 4 by 5-inch Polaroid® back and modified with a 45.5-cm tube to extend the focal length. This modification gives approximately a 4x magnification on the photograph. The photograph of the strand is then measured with a magnifying comparator, and memory is calculated by the previously mentioned equation.

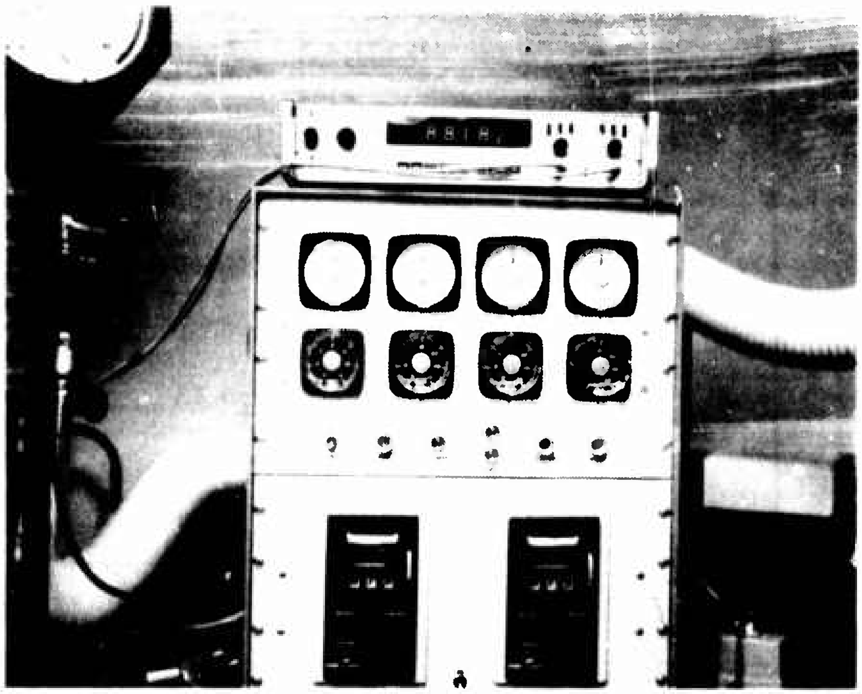

Figure 8 H/P 5325B Electrical Counter

TECHNIQUES

The high volatility and viscous nature of the polymer solutions studied caused problems in loading the rheometer barrel. The procedure used for filling of the barrel must minimize solvent losses and the solution must contain no voids or air bubbles. The technique developed for barrel loading utilized a modified 30 cc disposable syringe fitted with a nominal 0.48 cm x 15.25 cm I. D. piece of Teflon® tubing, as shown in Figure 9. The sample jar is fitted with a modified lid containing a Swagelok® fitting for tube insertion. The jar is inverted and the syringe filled through this fitting, thus minimizing the solvent loss. The Teflon® tubing is then slipped onto the end of the syringe and the tubing inserted to the bottom of the barrel. The tube is slowly removed as the barrel is filled. When filled, the barrel is sealed with either a rubber stopper or the Teflon® tipped ram. For solutions of low viscosity, the capillary tip is plugged with a round wooden toothpick to prevent solvent losses. The solution is allowed to equilibrate for 5 minutes prior to a run at 23.9°C (75°F) and for 10 minutes prior to a run at 10°C (50°F) or lower.

The orifice is removed and cleaned between each run with a wire reamer and solvents. The barrel is cleaned with a 20-gauge gun barrel cleaner and a soft cloth. After cleaning, the barrel is closed to prevent water condensation at lower temperatures.

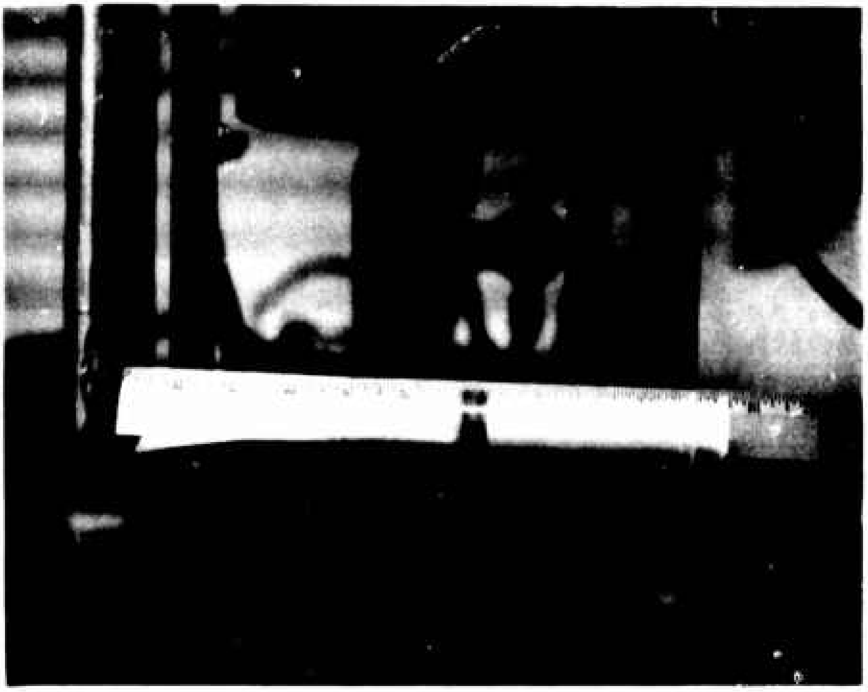

Figure 9. Modified Syringe with Tubing

MATERIALS

The Napalm B used in the study was prepared in the laboratory in accordance with the Air Force Armament Laboratory Purchase Description Assignment No. 5, Napalm B, dated 27 April 1966, or procured from Atlas Fabricators, Inc., Torrence, California, as a part of a large purchase of production material for use in filling experimental weapons. Napalm B is composed of polystyrene (46% $\pm$ 1.0%), gasoline (33% $\pm$ 1.0%) and benzene (21% $\pm$ 1.0%). Regular-grade gasolines were used; most of them contained lead and were obtained from the Eglin Air Force Base motor pool or from local service stations. The polystyrene used was DOW 666, obtained from Dow Chemical Company.

The styrene-butadiene copolymers (SBR) were obtained from the B. F. Goodrich Chemical Company. The two SBRs used in this study were Ameripol® 1513, designated SBR 40 (contains 40 percent styrene) and Ameripol® 1013, designated SBR 43 (contains 43 percent styrene). Solutions of the SBRs were prepared containing a total of 20 percent of one of the copolymers, 43.7 percent gasoline, and 27.3 percent benzene.

The styrene-methylmethacrylate (NAS) used was obtained from the Richardson Company. Solutions were prepared containing 40 percent NAS, 36.9 percent gasoline, and 23.1 percent benzene.

In order to minimize variations in the solutions and eliminate any possible shear degradation of the polymers by mixing, all solutions were prepared by adding the required components to a glass jar, sealing the lid with tape to minimize solvent losses, and slowly rotating the jars on an approximately 66-cm diameter wheel. From two to three days were required to obtain clear solutions with no indications of undissolved material. As an additional check for solvent loss, the prepared samples were weighed before and after mixing.

DATA REDUCTION

The pressure applied for extrusion, the time required for the extrusion, strand diameter measured from the photograph, and the temperature are required for each data point. The data, along with the capillary dimensions and the fixed volume extruded, are used to calculate the shear stress, shear rate, apparent viscosity, and percent memory using a CDC 6600 computer. The computer program is included as Appendix A.

The data generated is presented in graphical form as log-log plots of shear stress versus shear rate and apparent viscosity versus shear rate and semi-log plots of percent memory versus shear rate.

Final curves for the plots of apparent viscosity versus shear rate are determined from a least square analysis of the data points as a part of the computer program.

SECTION IV

RESULTS AND DISCUSSION

CALIBRATION OF EQUIPMENT

In order to verify the uniformity of results from the various capillaries used in the study, a series of runs were carred out using each of the capillaries to measure the viscosity of the same solution. The results of these runs at 23.9°C (75°F) on a sample of Napalm B formulated with regular grade gasoline are shown in Figure 10. All of the data points are well within normal experimental error. This data verifies both the reproducibility of the capillaries and the techniques used to handle the solution and load the rheometer barrel.

Another problem which must be considered is the reproducibility of solution preparation. In order to verify the reproducibility of mixing techniques, three separate solutions of Napalm B formulated with regular grade gasoline were prepared. Figure 11 shows the data obtained from these solutions.

COMPARISON OF RECOVERABLE SHEAR AND MEMORY

The type data obtained from recoverable shear and percent memory determinations can best be illustated by comparing the results of the two methods on the same solution. Figure 12 shows a comparison of the results of the two methods, using Napalm B at 23.9°C as an example. While the numerical values obtained from the two methods are quite different, both values increase as the shear rate is increased. As can be seen from the lines in this figure, the change in memory with increasing shear rate is near linear, while the change in recoverable shear is more drastic and appears to be a logarithmic-type function.

RHEOLOGICAL BEHAVIOR OF NAPALM B

Flow curves (viscosity as a function of shear rate) were prepared for Napalm B at six different temperatures from -6.7°C (20°F) to 60°C (140°F). The results of these experiments, using a production lot of Napalm B, are shown in Figure 13. As has previously been discussed, polystyrene (and thus Napalm B) is a thermoplastic material; that is, its rheological behavior varies as a function of temperature. For the solution studied, the viscosity increases by a factor of about five as the temperature is decreased from 60°C to -6.7°C. The curves obtained are similar to those obtained by Gaskins[2] at Edgewood Arsenal and Long[3,4] at Monsanto Research Corporation. Small differences in this data and previous data can easily be attributed to actual differences in the solutions, since Long has observed considerable variations from different samples of

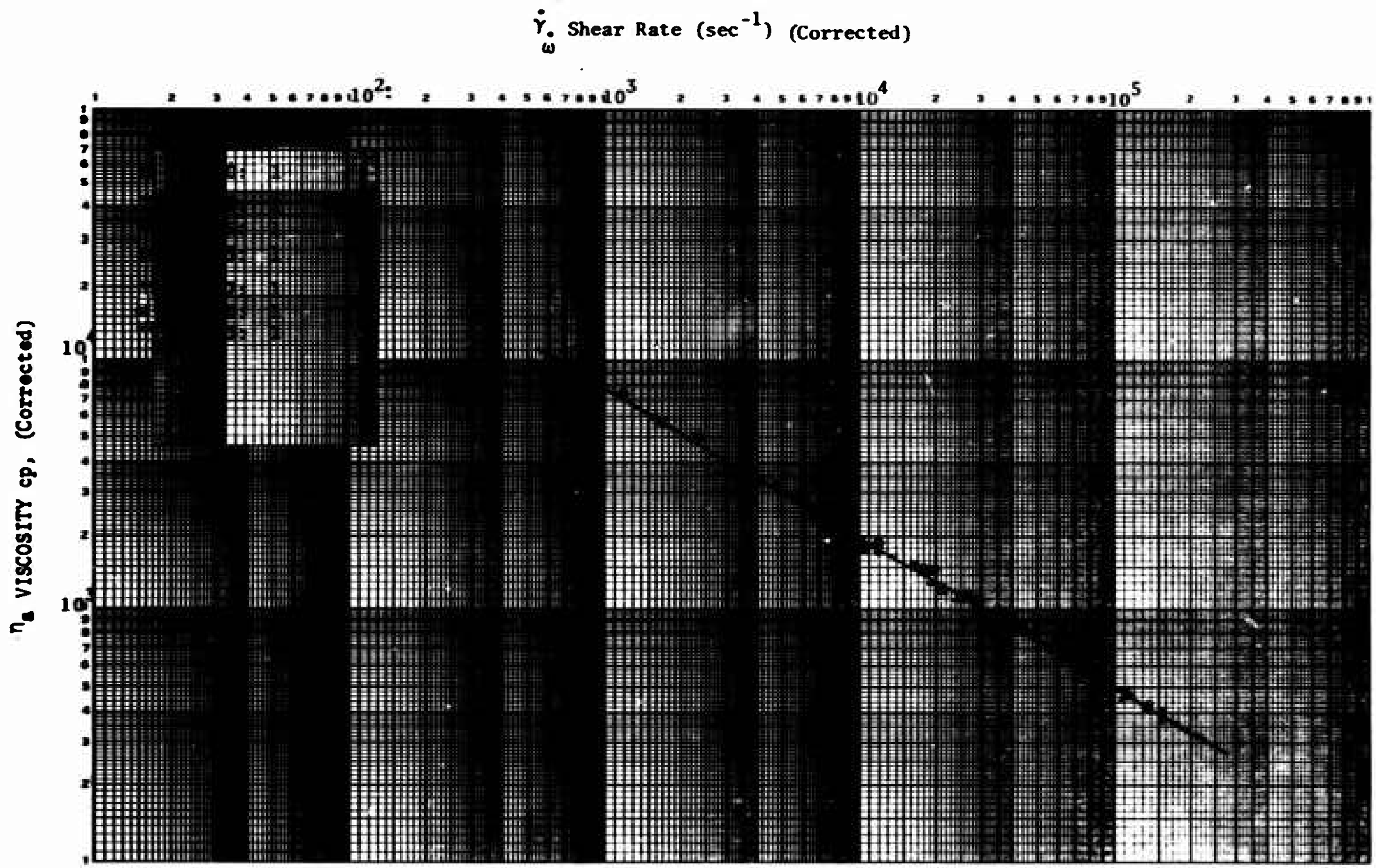

Figure 10. Flow Curves of Various Capillaries for Napalm B

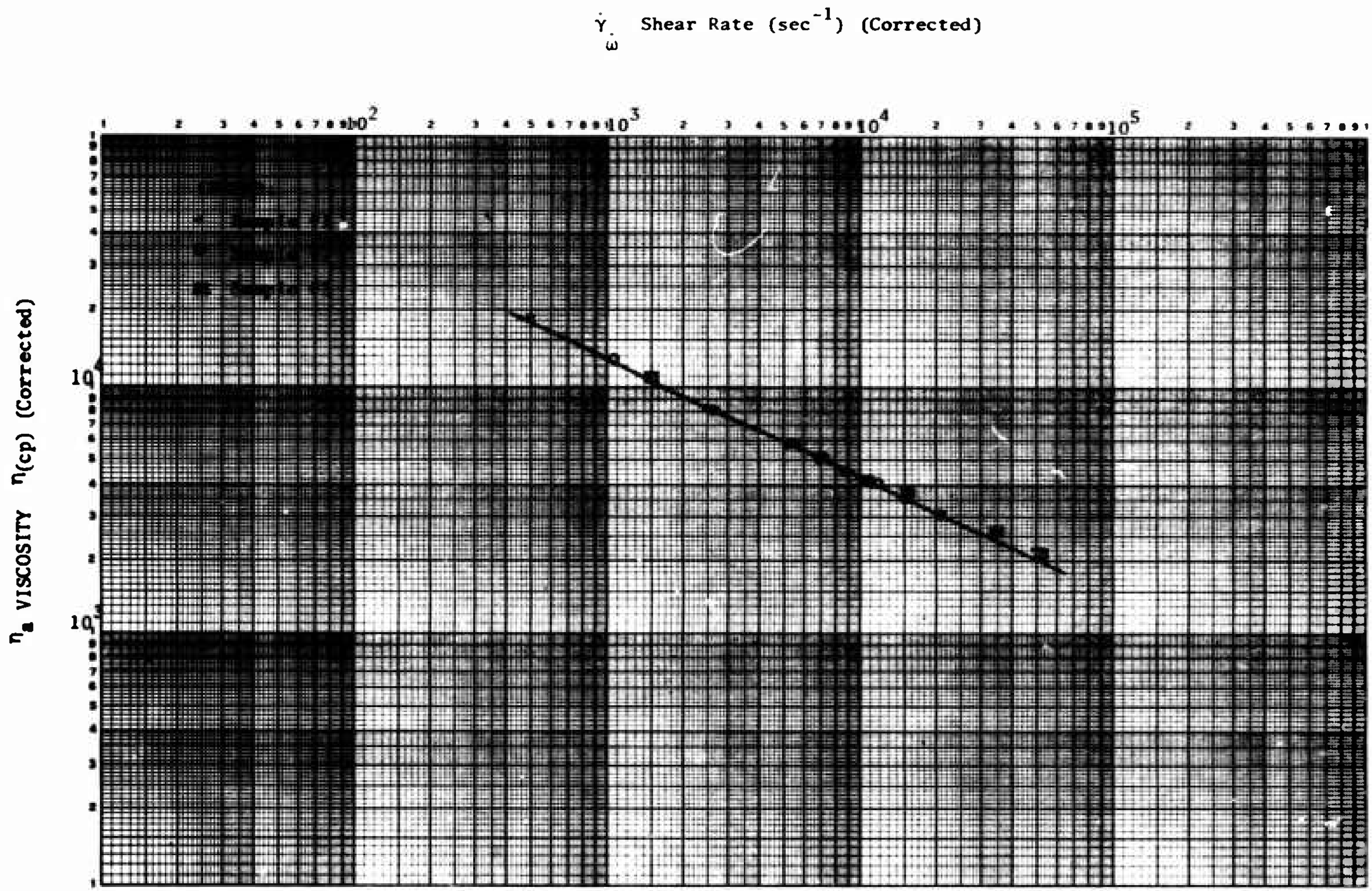

Figure 11. Flow Curve for Napalm B with Chevron Gasoline at OC (32°F)

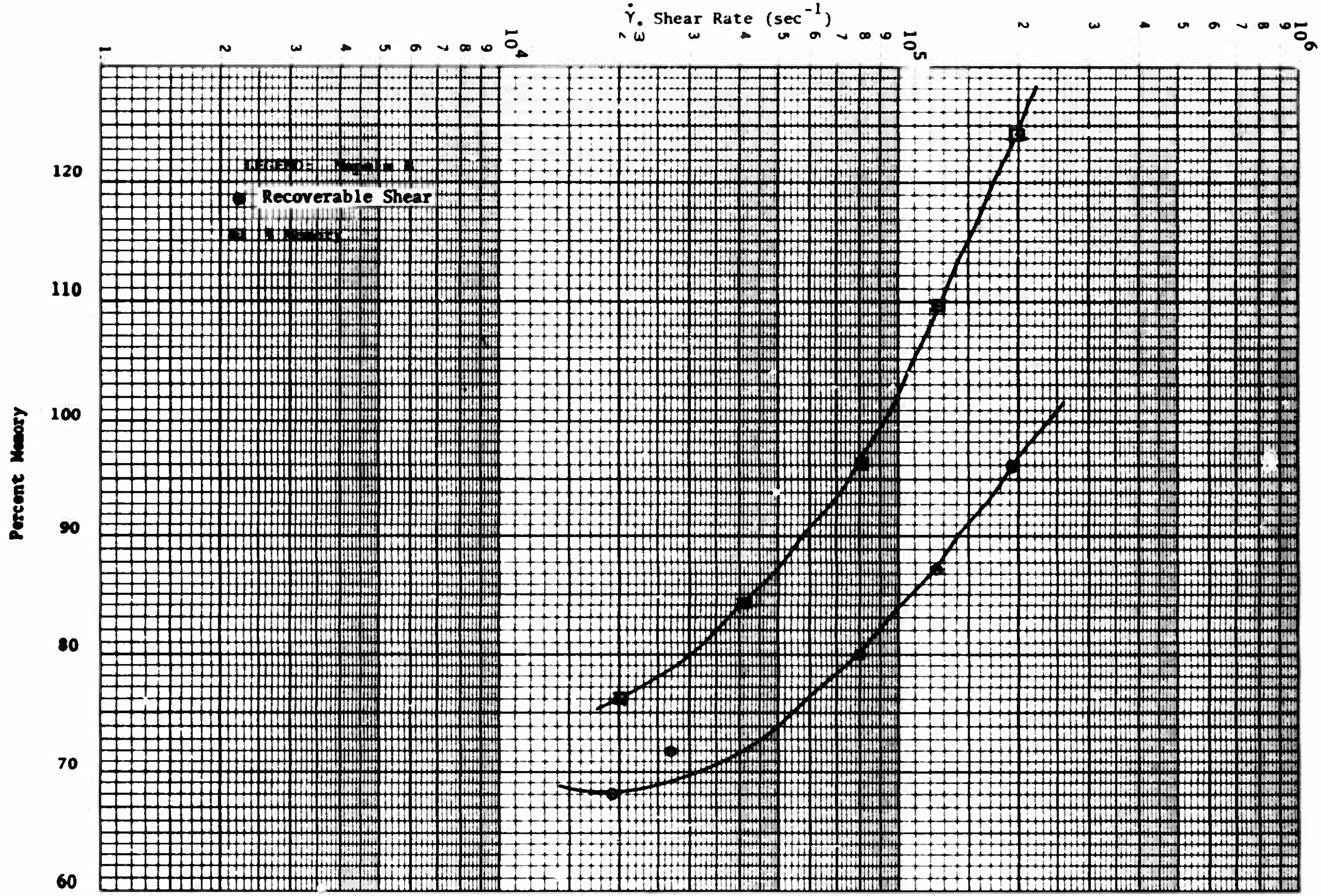

Figure 12. Comparison of Percent Memory and S_r for Napalm B

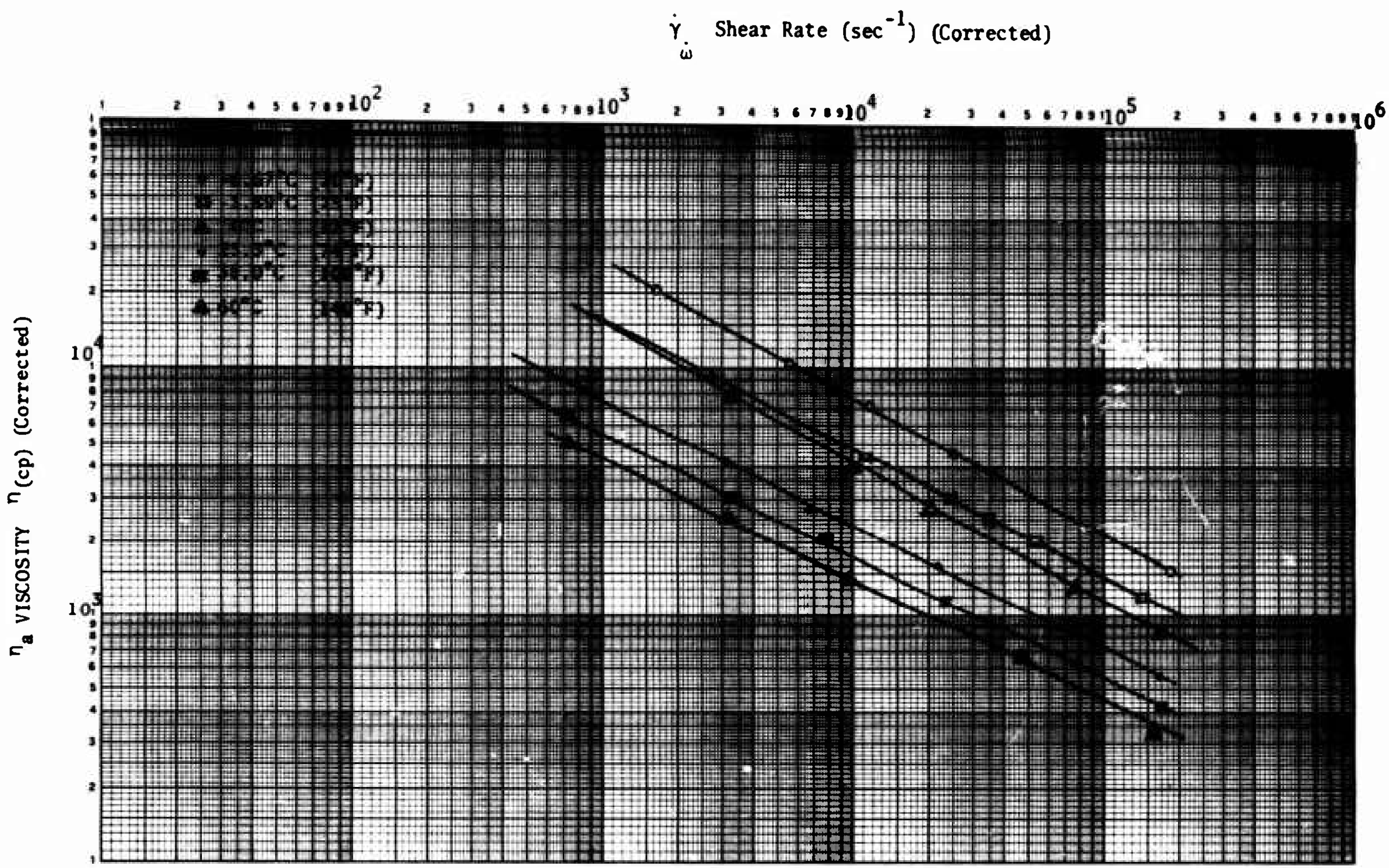

Figure 13. Flow Curve for a 46 Percent Styrene-Methylmethacrylate at 23.9°C

the production lot of Napalm B. These results show that the change in viscosity over the shear rate range of 10^3 sec^{-1} to 10^5 sec^{-1} is linear, as compared to the same curvature in the lines reported in previous efforts[2, 3]. Since the primary interest is in the high shear forces during fuel dissemination where a bomb case opens, the lower shear rate range is not of interest to our application and no attempt was made to collect data below 10^2 sec^{-1}.

Figure 14 shows the percent memory of Napalm B as a function of shear rate at -3.89°C and 23.9°C. As was the case for the viscosity, the thermoplastic behavior is evident from the considerable difference in the memory at the two temperatures.

The solvent system used to prepare the polystyrene solution has a definite effect on the rheological properties of the solution. To illustrate this, several Napalm B formulations were prepared using different brands of gasoline. The percentages of polystyrene, benzene, and gasoline were constant so the only variable was the brand of the gasoline. Figures 15 and 16 show the effects of various gasolines on the viscosity and memory. Some of the gasolines used did not appear to form a true solution and were not included in the reported studies. As can be seen in the figures, the type of behavior (in the shape and slope of the curves) is the same for the different formulations. However, the absolute values of viscosity and memory are somewhat different for the various gasolines. This behavior emphasizes the importance of controlling experimental variables in a precise laboratory study and illustrates one of the major problems when data from various laboratories is compared.

RHEOLOGICAL BEHAVIOR OF EXPERIMENTAL FORMULATIONS

In previous efforts[3, 4] several experimental formulations have been evaluated as candidate flame fuels. Three of these formulations are included in this report to illustrate the investigation of different polymer solutions with different properties by this technique.

Figures 17 and 18 show the properties of a 40 percent styrene-methyl-methacrylate (NAS) solution. The elastic properties of this solution are very similar to those of Napalm B, as shown in Figure 18. The viscosity is slightly less dependent on shear rate than that of Napalm B; i.e., the viscosity versus shear rate curve is more horizontal. In addition, the temperature dependence is even more pronounced than for Napalm B. Based on this information, it would be predicted that NAS would be equal to or slightly better than Napalm B at 75°F; however, the increased viscosity at 25°F indicates that the performance would be inferior at low temperatures.

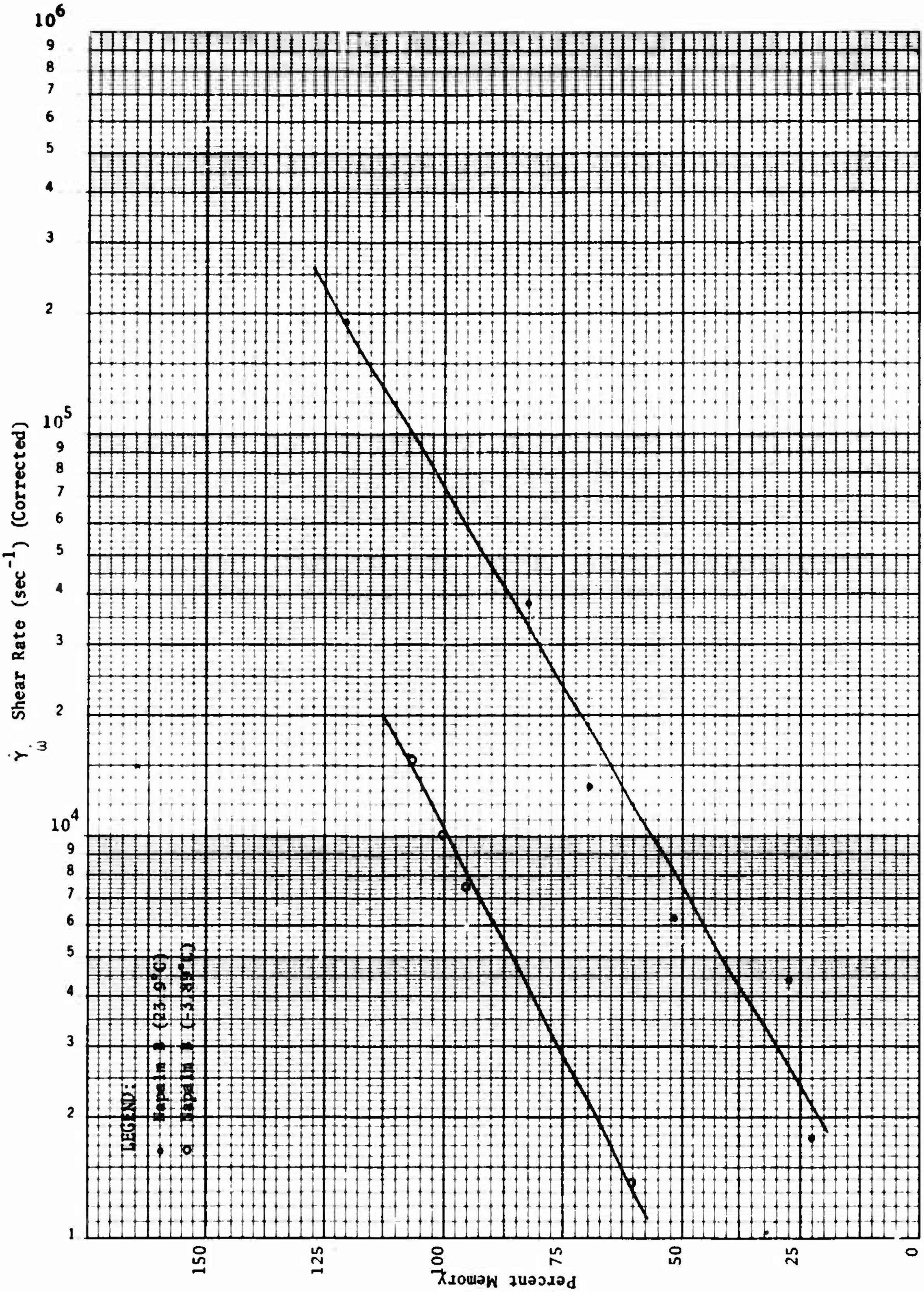

Figure 14. Percent Memory of Napalm B (Dow Mixed)

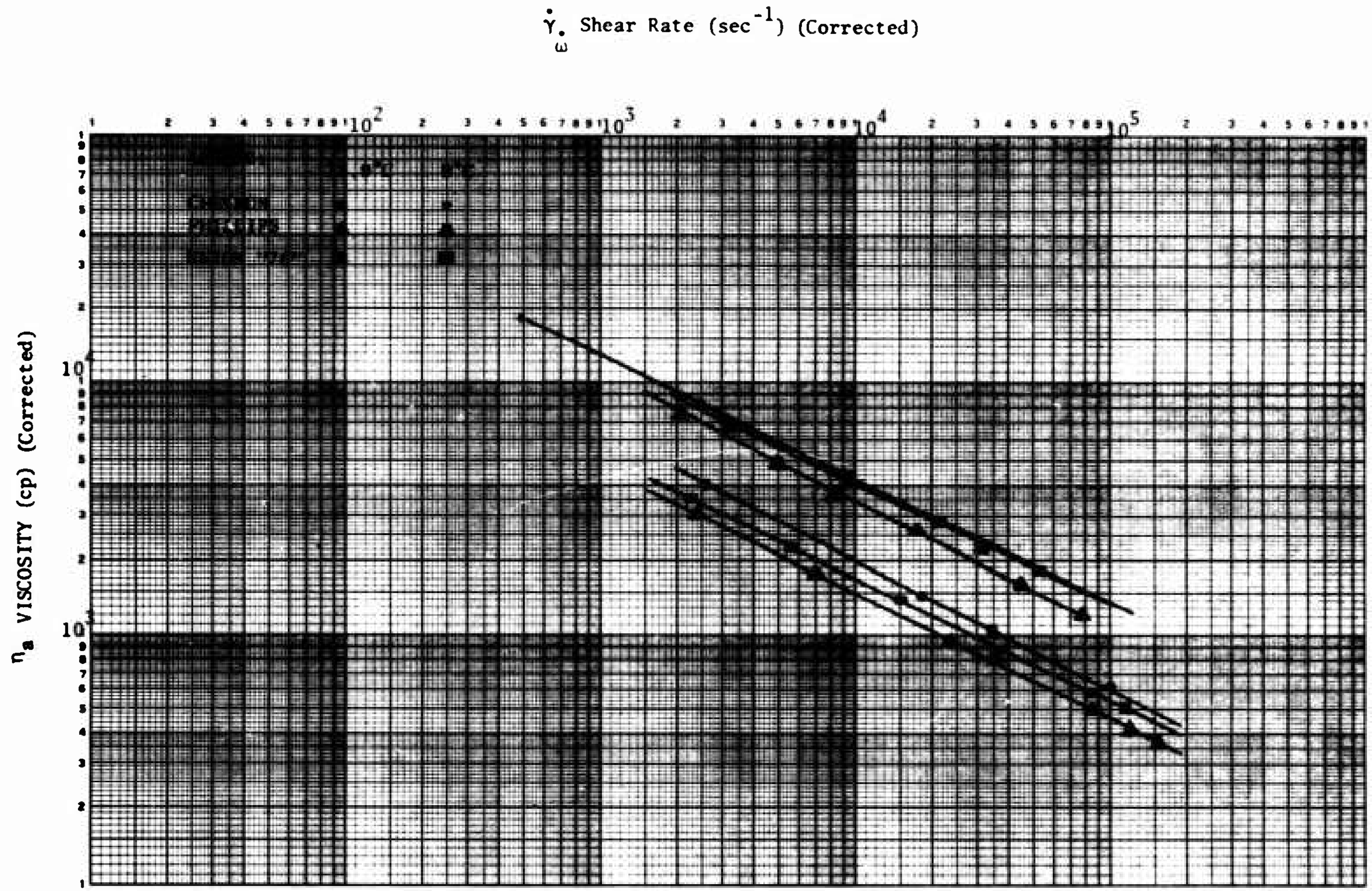

Figure 15. Flow Curve of Napalm B Formulated with Various Gasolines

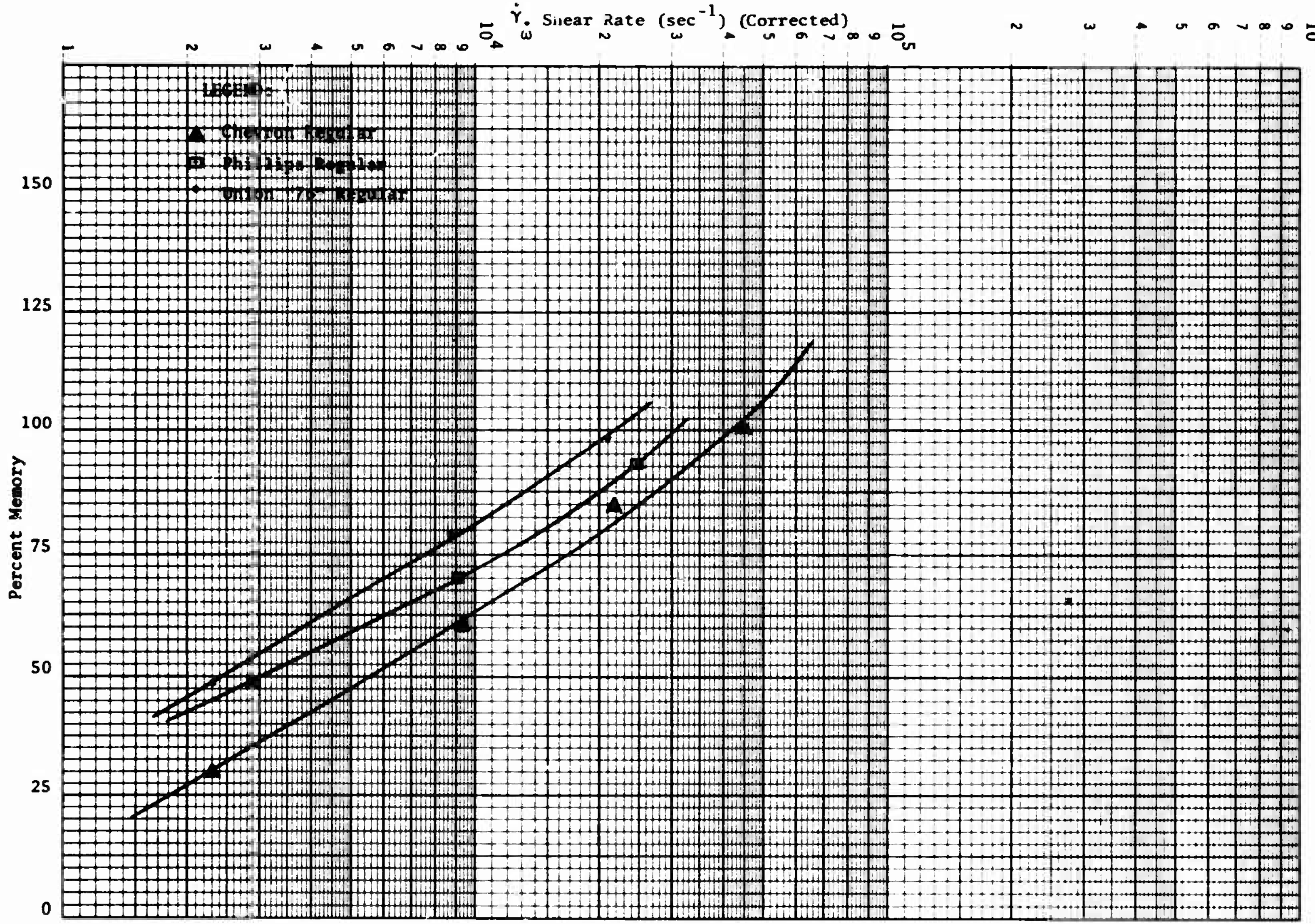

Figure 16. Percent Memory of Various Gasolines and Polystyrene Formulations

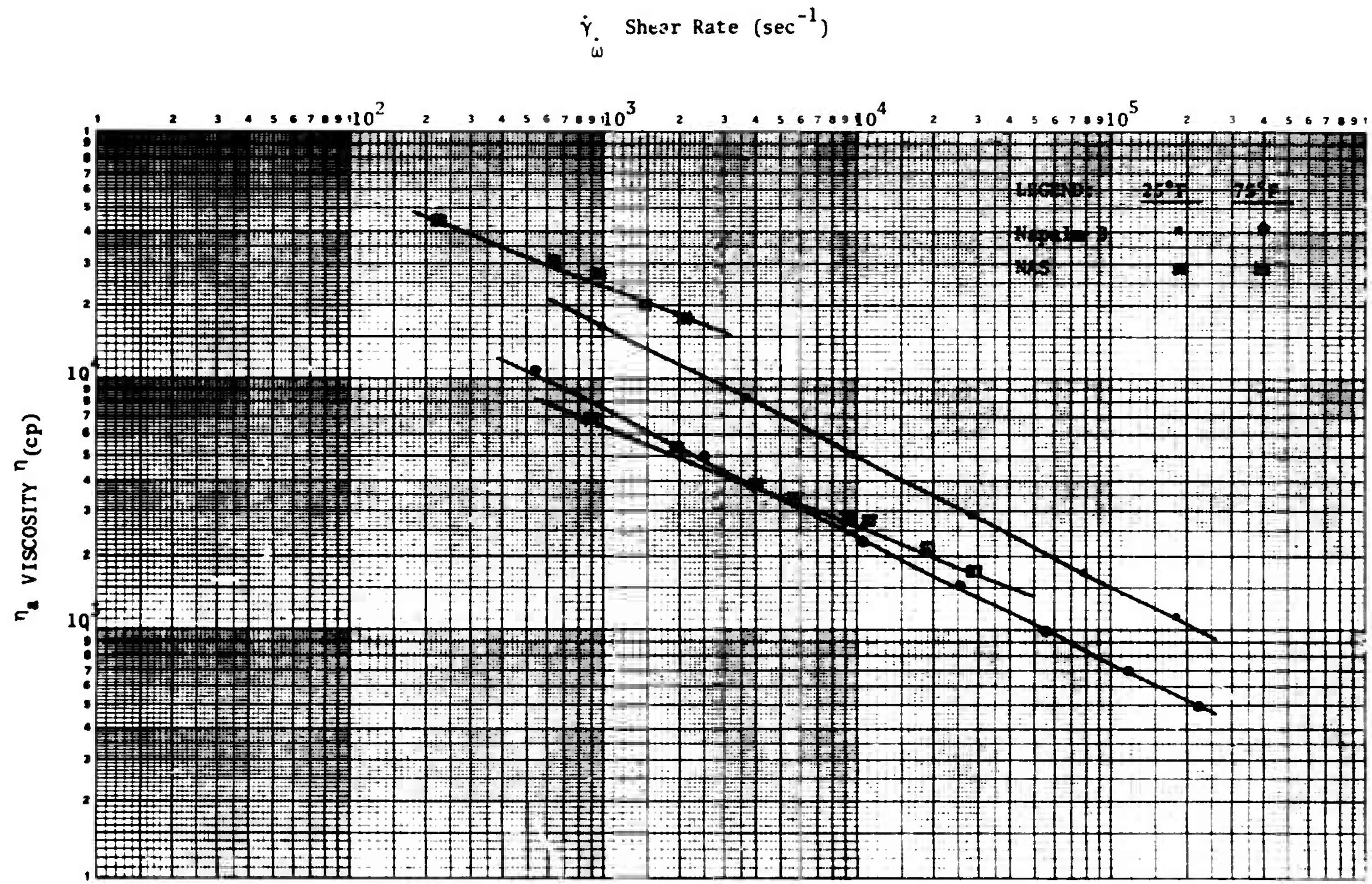

Figure 17. Flow Curve of Napalm B and Styrene-Methylmethacrylate at 25°F and 75°F

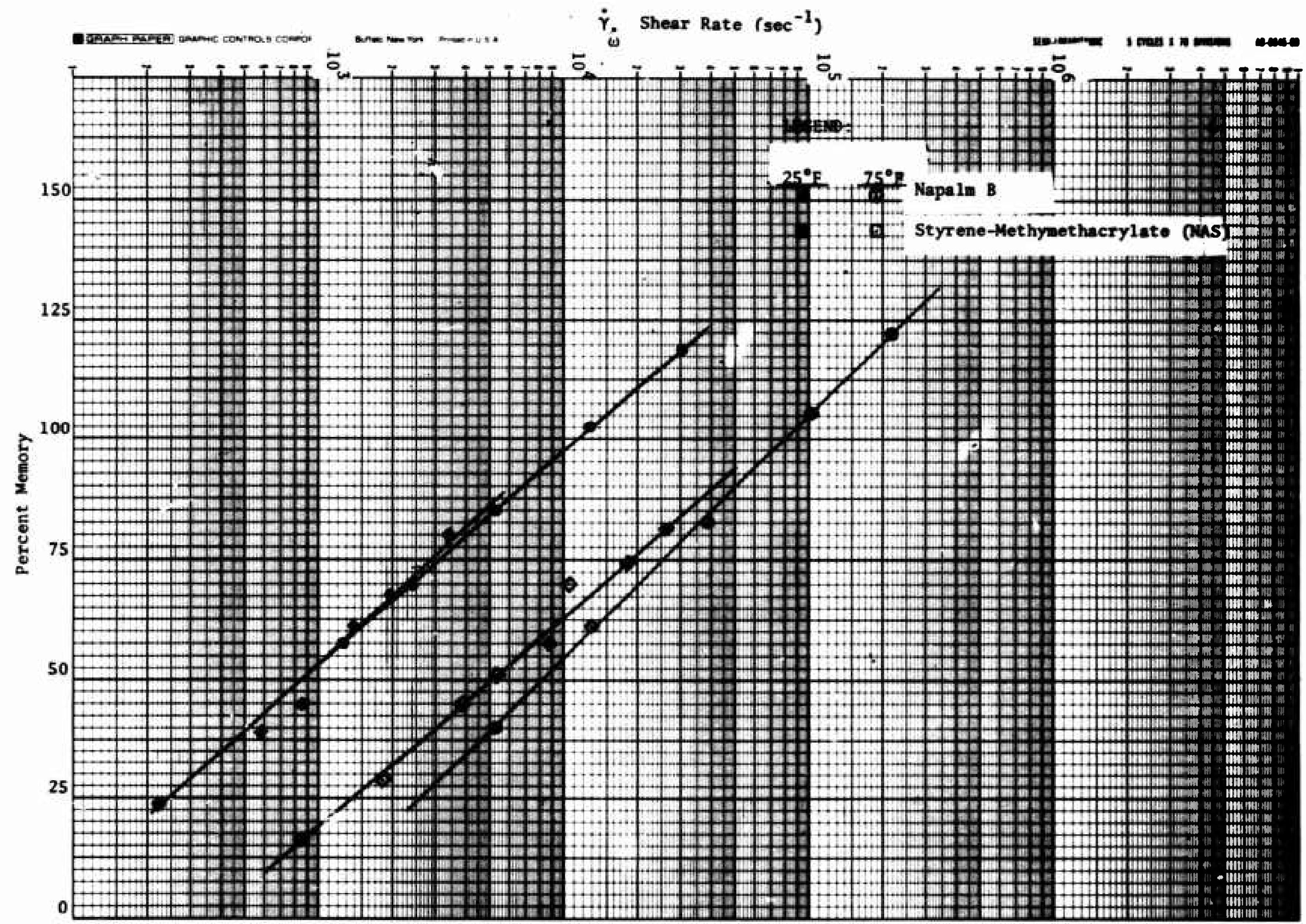

Figure 18. Comparison of Percent Memory for Napalm B and a 40 Percent Formulation of Styrene-Methylmethacrylate (NAS)

The most promising candidate materials investigated to date have been the styrene-butadiene (SBR) copolymers. The viscoelastic properties of these rubber-like materials are considerably less temperature dependent than the properties of a thermoplastic material like polystyrene. In addition, the viscosity and elasticity can be varied by changing the percentage of styrene in the copolymer and by altering the molecular weight distribution.

The properties of a 29 percent solution of SBR 40 (containing 40 percent styrene) are shown in Figures 19 and 20. Although the viscosity is lower than that of Napalm B, it is significantly less temperature dependent. The elastic properties are almost independent of the shear rate, contrasting sharply to the steep shear rate dependence of Napalm B.

Figures 21 and 22 show the properties of a 29 percent solution of SBR 43 (containing 43 percent styrene). The rheological properties are very similar to those observed for SBR 40, except the absolute value of percent memory is higher; that is, the solution has a greater elastic strength.

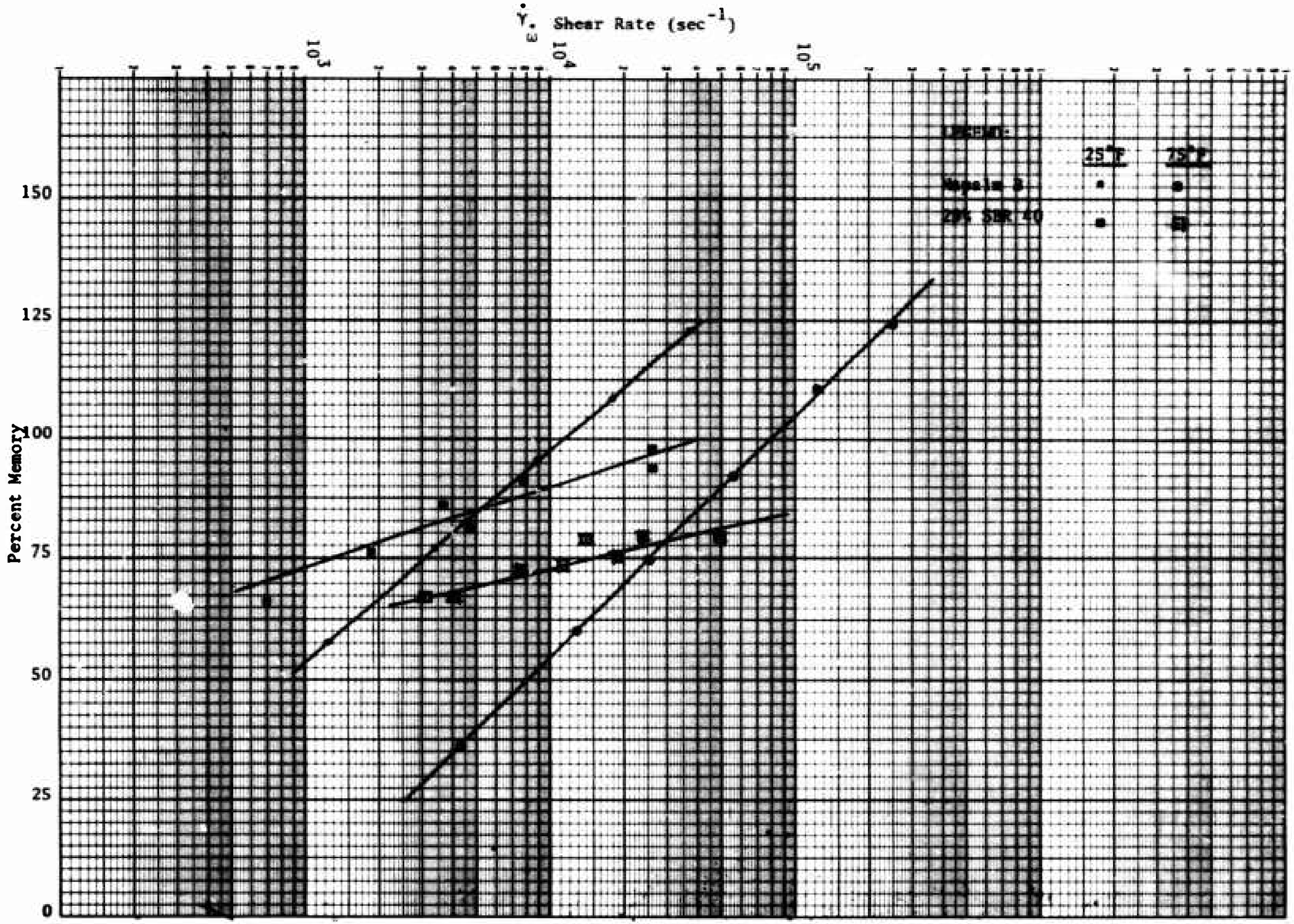

Figure 19. Comparison of Percent Memory for Napalm B and 29 Percent SBR 40 Solution

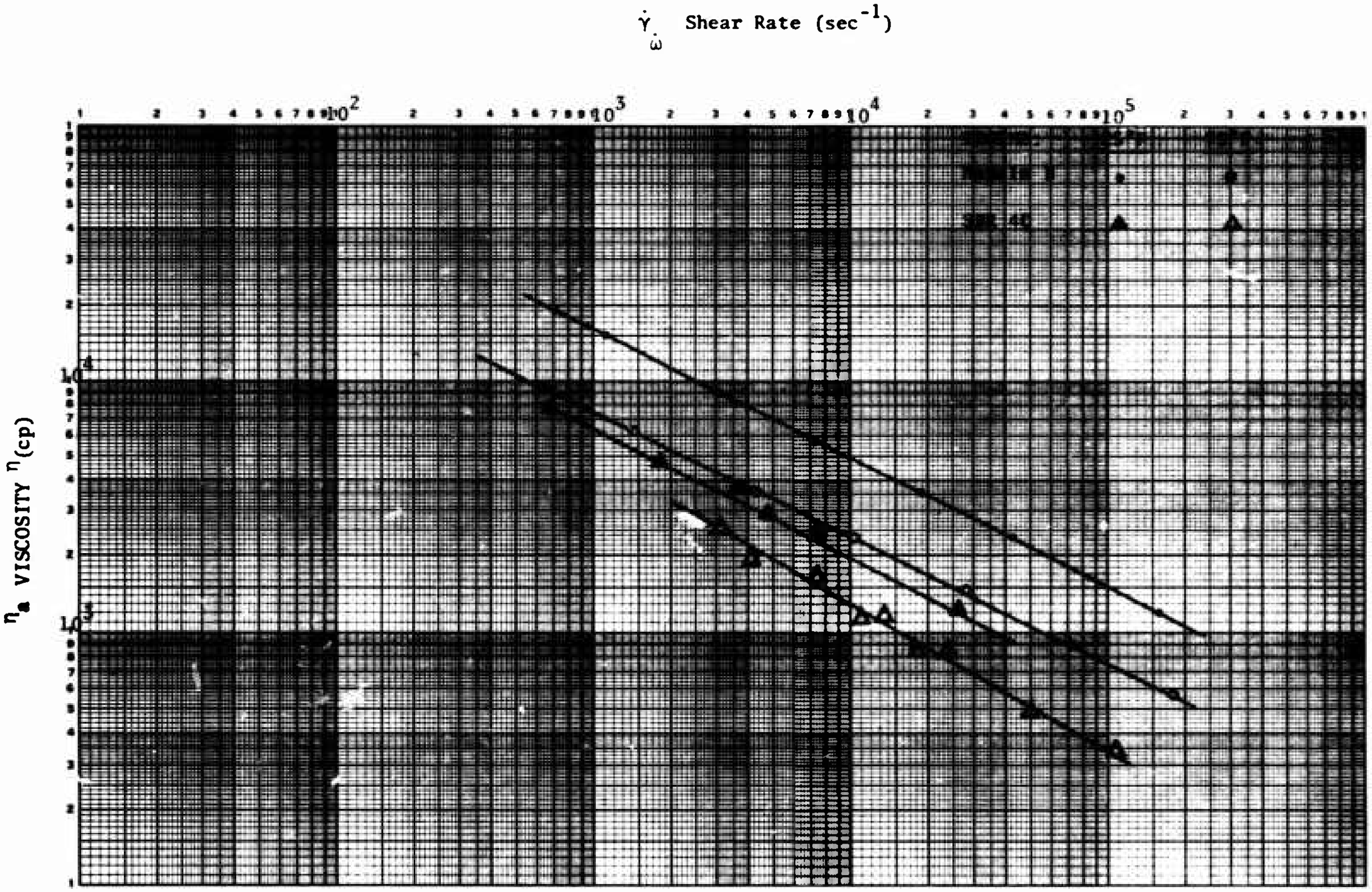

Figure 20. Comparison of Viscosity versus Shear Rate of 29 Percent SBR 40

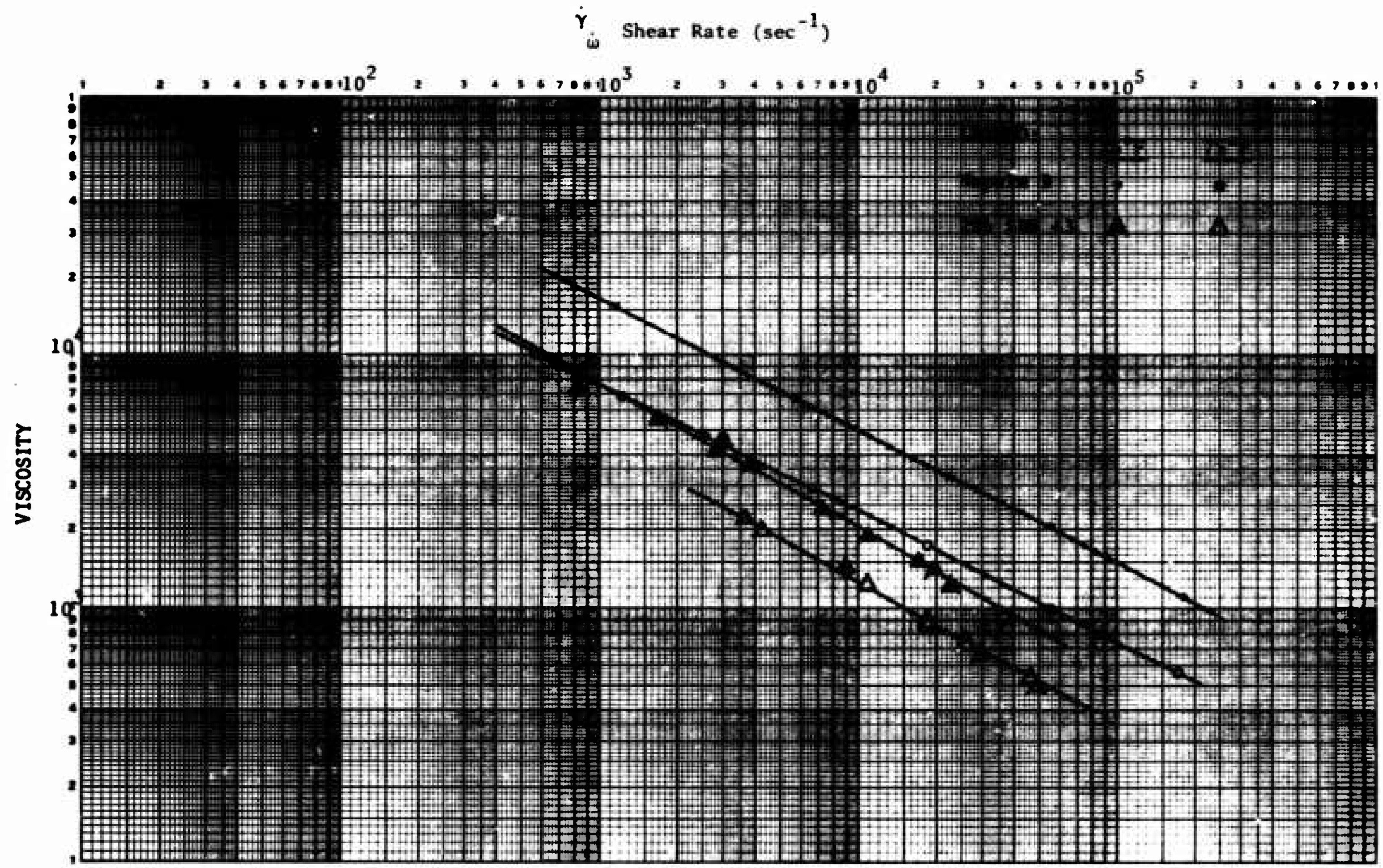

Figure 21. Comparison of Viscosity for Napalm B and a 29 Percent SBR 43 Formulation

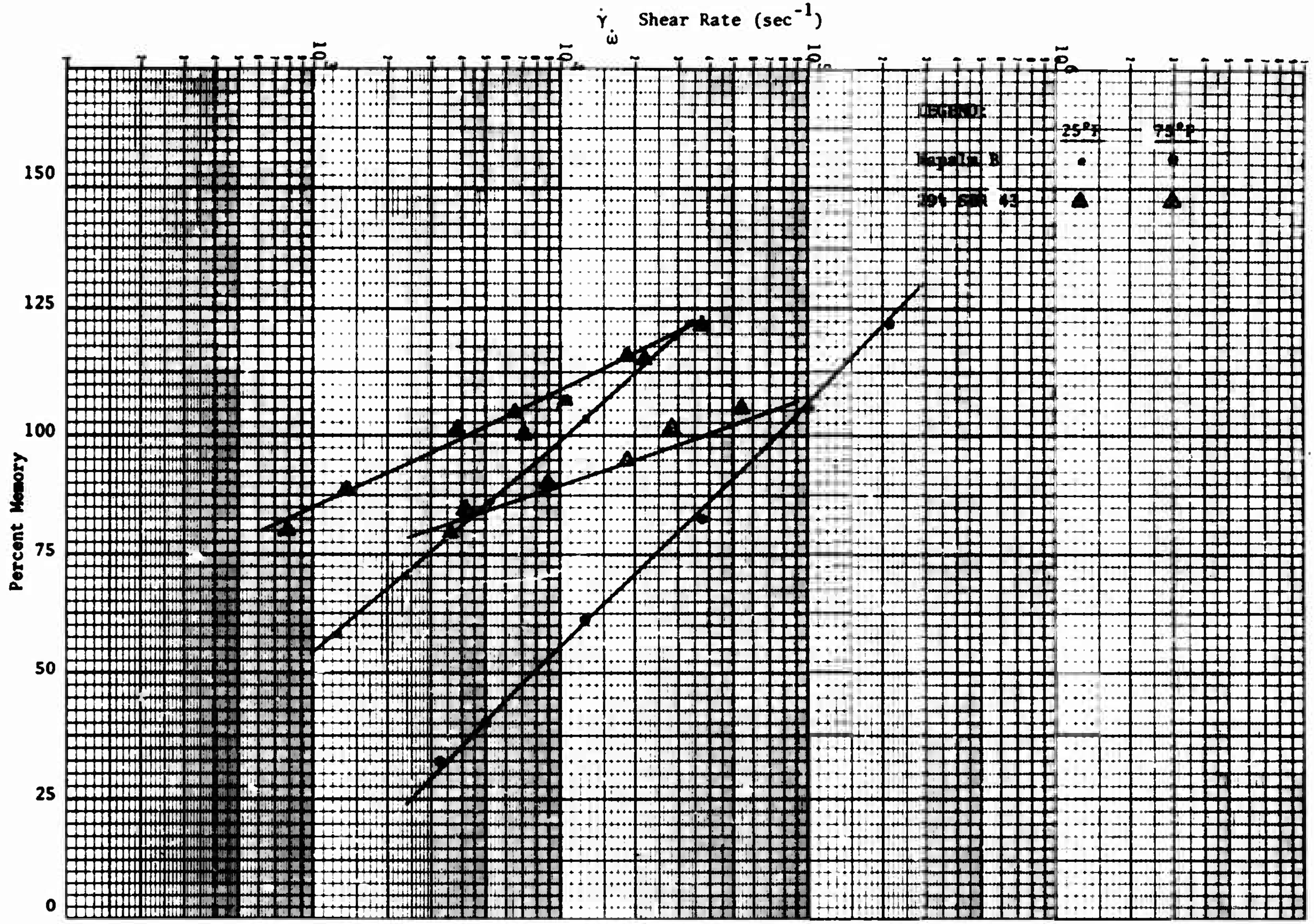

Figure 22. Comparison of Percent Memory for Napalm B and 29 Percent SBR 43 Formulation

SECTION V

SUMMARY AND CONCLUSIONS

The instrumentation and techniques developed during this study represent a significant advancement in the Air Force capability for development of improved flame agents for use in firebombs. The study has shown that a capillary extrusive rheometer can be utilized to measure the rheological properties of polymer solutions with viscosities in the range of 10^2 to 10^5 centipoise at shear rates from 10^2 to 10^6 sec^{-1}, as a function of temperature from 25°F to 100°F.

The rheological behavior of a given polymer solution can be utilized to predict the dynamic behavior of the material during dissemination from a firebomb. Thus, this laboratory-scale technique can be used to screen candidate firebomb fuels.

While either the die swell or recoverable shear methods may be used to study the elastic properties of a solution, the die swell method has been shown to be a much faster and simpler method of obtaining the desired information.

The solvent system used in preparation of a solution has been shown to have an effect on the values of viscosity and elasticity of a solution but not on the shapes of the curves. A series of curves obtained for solutions prepared with different brands of gasoline are parallel but offset in the value of viscosity or elasticity. These results emphasize the importance of using a standardized gasoline or gasoline simulant when data from different techniques or different laboratories are compared.

The rheological properties of solutions of the styrene-butadiene copolymers (SBR) have been shown to be less dependent on temperature or shear rate than thermoplastics, such as polystyrene.

More data are required to determine the extent of shear degradation with a given viscoelastic property. However, the test used did not attempt to measure all the controlling parameters encountered in dynamic air gun and sled track tests. It should be recognized that the test used in this study was designed for laboratory purposes and does not necessarily predict the field behavior of the agent when exposed to various means of dissemination.

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APPENDIX A

CAPILLARY EXTRUSION RHEOLOGY DATA REDUCTION PROGRAM 1939

```
      PROGRAM P1939(INPUT,OUTPUT,FILMPL,TAPE1,TAPE8)                    P1939         2
      DIMENSION SAMPLE(6),FORCE(20),TIME(20),CAPD(30),Q(20),T(20),D(20), P1939         3
     1 DIA(20),TLOG(20),DLOG(20),SRC(20),           VISN(29),CAPT(30)   P1939         4
      DIMENSION BVOL1(20)                                               P1939         5
      COMMON /FIT1/ B                                                   P1939         6
      DIMENSION PERM(20)                                                P1939         7
      COMMON NOF,XMAX,XMIN,YMAX,YMIN                                    P1939         8
      EXTERNAL TABL1V                                                   P1939         9
      DATA (CAPD(I),I=1,19)/ 5.22,39500.,148000.,311000.,16600000.,     P1939        10
     1 377000.,377000.,377000.,1274000.,1274000.,1274000.,10192000.,    P1939        11
     210192000.,10192000.,1274000.,10190000.,1274000.,10190000.,        P1939        12
     3 10190000. /                                                      P1939        13
      DATA (CAPT(I),I=1,19) / 388300.,15530.,19350.,4882.,1774.,4643.,  P1939        14
     1 6208.,9318.,6237.,4147.,3112.,3137.,2071.,1548.,60890.,31060.,   P1939        15
     2 1239.,621.2,15380./                                              P1939        16
C     THE ORDER OF STORAGE OF CONSTANTS FOR CAPILLARIES-                P1939        17
C (1)4-1      (2)10-1     (3)15-1     (4)33-1     (5)68-1     (6)33.45-1 P1939       18
C (7)25-1     (8)16.66-1  (9)24.9-1   (10)37.45   (11)49.9-1  (12)49.5-1 P1939       19
C(13)75-1    (14)100-1   (15)2.55-1  (16)5-1     (17)127.49  (18)249.9-1 P1939       20
C(19)10.1-1                                                             P1939        21
      WRITE(8,5)                                                        P1939        22
      REWIND 1                                                          P1939        23
      ASSIGN 150 TO IEOF                                                P1939        24
   11 LINE = 0                                                          P1939        26
      PRINT 5                                                           P1939        27
    5 FORMAT(1H1)                                                       P1939        28
   19 READ 1,ITEMP,CAP,CLEN,CDIA,IC,IM,IY,SAMPLE                        P1939        29
      IF(EOF(1).NE.0.0) GO TO 999                                       P193900       1
    1 FORMAT(I3,A7,2F5.4,A2,A3,A2,5A10,A3)                              P1939        31
      READ 2,BVOL,ODIA,ICAP,IREC                                        P1939        32
      IF(EOF(2).NE.0.0) GO TO 150                                       P193900       2
    2 FORMAT(2F10.5,2I5)                                                P1939        33
      I = 1                                                             P1939        34
   20 READ 3,FORCE(I),TIME(I),DIA(I),BVOL1(I)                           P1939        35
      IF(EOF(3).NE.0.0) GO TO 150                                       P193900       3
      IF(FORCE(I).EQ.0.) GO TO 25                                       P1939        36
      I = I+1                                                           P1939        37
      GO TO 20                                                          P1939        38
   25 NOF = I-1                                                         P1939        39
    3 FORMAT(4F10.0)                                                    P1939        40
C   CALCULATE Q - VOLUMETRIC FLOW                                       P1939        41
      DO 30 I=1,NOF                                                     P1939        42
      IF(BVOL.GT.0.) Q(I) = BVOL/TIME(I)                                P1939        43
      IF(BVOL.LE.0.) Q(I) = BVOL1(I)/TIME(I)                            P1939        44
```

```
C CALCULATE SHEAR STRESS                                                P1939
      T(I) = FORCE(I)*CAPT(ICAP)                                        P1939
C  CALCULATE APPARENT RATE OF SHEAR AT WALL                             P1939
      D(I) = Q(I)*CAFD(ICAP)                                            P1939
   30 CONTINUE                                                          P1939
C  CONVERT SHEAR STRESS(T) AND SHEAR RATE (D) TO LOG NUMBERS FOR PLOTS  P1939
C  T - X AXIS     D - Y AXIS                                            P1939
      DO 35 I=1,NOF                                                     P1939
      TLOG(I) = ALOG10(T(I))                                            P1939
   35 DLOG(I) = ALOG10(D(I))                                            P1939
C                                                                       P1939
C  PRINT OUT OF POINTS THAT ARE PLOTTED.                                P1939
      WRITE(8,8) CAP,(TLOG(I),I=1,NOF)                                  P1939
      WRITE(8,9) (DLOG(I),I=1,NOF)                                      P1939
    8 FORMAT(1H0,9X,*CAPILLARY  *,A7/10X,*X = *,3X,(10F8.4))            P1939
    9 FORMAT(10X,*Y = *,3X,(10F8.4))                                    P1939
C                                                                       P1939
      CALL MAXMIN(TLOG,DLOG)                                            P1939
      IF(IREC.EQ.1) WRITE(1) NOF,(TLOG(I),I=1,NOF),XMIN,XMAX,CAP,CLEN   P1939
C                                                                       P1939
C  PLOT OF LOG SHEAR STRESS VS LOG SHEAR RATE                           P1939

      CALL SETMIV(100,54,54,100)                                        P1939
      LL = 1                                                            P1939
      LLL = 1                                                           P1939
      IF((XMAX-XMIN).GT.2.) LL = 2                                      P1939
      IF((YMAX-YMIN).GT.2.) LLL = 2                                     P1939
      XMAX = XMAX+.10000                                                P1939
      YMAX = YMAX+.20000                                                P1939
      CALL SMXYV(0,0)                                                   P1939
      CALL GRIDIV(3,XMIN,XMAX,YMIN,YMAX,.1,.1,1,1,LL,LLL,3,3)           P1939
C                                                                       P1939
C                                                                       P1939
      CALL CHSIZV(2,2)                                                  P1939
      CALL RITSTV(13,19,TABL1V)                                         P1939
C  HORIZONTAL                                                           P1939
      CALL RITE2V(400,30,1024,90,1,20,-1,20HLOG T - SHEAR STRESS,NL)    P1939
C  VERTICAL                                                             P1939
      CALL RITE2V(10,689,1024,90,1,1,-1,1HL,NL)                         P1939
      CALL RITE2V(10,670,1024,90,1,1,-1,1HO,NL)                         P1939
      CALL RITE2V(10,651,1024,90,1,1,-1,1HG,NL)                         P1939
      CALL RITE2V(10,613,1024,90,1,1,-1,1HD,NL)                         P1939
      CALL RITE2V(10,575,1024,90,1,1,-1,1H.,NL)                         P1939
      CALL RITE2V(10,537,1024,90,1,1,-1,1HS,NL)                         P1939
      CALL RITE2V(10,518,1024,90,1,1,-1,1HH,NL)                         P1939
      CALL RITE2V(10,499,1024,90,1,1,-1,1HE,NL)                         P1939
```

```
      CALL RITE2V(10,480,1024,90,1,1,-1,1HA,NL)
      CALL RITE2V(10,461,1024,90,1,1,-1,1HR,NL)
      CALL RITE2V(10,423,1024,90,1,1,-1,1HR,NL)
      CALL RITE2V(10,404,1024,90,1,1,-1,1HA,NL)
      CALL RITE2V(10,385,1024,90,1,1,-1,1HT,NL)
      CALL RITE2V(10,366,1024,90,1,1,-1,1HE,NL)
C
      CALL APLOTV(NOF,TLOG,DLOG,1,1,1,1H*,IERR)
      CALL APLOTV(NOF,TLOG,DLOG,1,1,1,1H*,IERR)
C
      CALL TITLE(ITEMP,CAP,CLEN,CDIA,ID,IM,IY,SAMPLE)
C
C
C
      CALL FIT(TLOG,CLCG)
C   COMPUTE CORRECTICN FACTOR
      CORF = (B+3.)/4.
      SSMIN = 999999.
C  COMPUTE CORRECTED RATE OF SHEAR AT WALL
      DO 45 I = 1,NOF
      SRC(I) = CORF*C(I)
      SSMIN = AMIN1(SRC(I),SSMIN)
   45 CONTINUE
      IF(IREC.EQ.1) WRITE(1) (SRC(I),I=1,NOF)
C  COMPUTE APPARENT CORRECTEC VISCOSITY AT WALL (VISN)-CENTIPOISE UNITS
      DO 50 I=1,NOF
   50 VISN(I) = T(I)/SRC(I)*100.
C
C  PLOT - VISN VS SRC ON LOG-LOG PAPER
C
C
C  Y-AXIS- VISN  X-AXIS - SRC
      CALL SETMIV(100,54,54,100)
      CALL SMXYV(1,1)
      XLIM = 1000.
      IF(SSMIN.LT.1000.) XLIM = 100.
      CALL GRID1V(3,XLIM,1000000.,100.,100000.,1.0,1.0,N,M,IXX,IYY,-2,
     1 -2)
      CALL APLOTV(NOF,SRC,VISN,1,1,1,1H*,IERR)
      CALL APLOTV(NOF,SRC,VISN,1,1,1,1H*,IERR)
      CALL TITLE(ITEMP,CAP,CLEN,CDIA,ID,IM,IY,SAMPLE)

C   VERTICAL AND HORIZCNTAL LABELS
      CALL RITE2V(10,744,1024,90,1,1,-1,1HN,NL)
      CALL RITE2V(10,706,1024,90,1,1,-1,1H.,NL)
      CALL RITE2V(10,668,1024,90,1,1,-1,1HA,NL)
```

```
      CALL RITE2V(10,649,1024,90,1,1,-1,1HP,NL)
      CALL RITE2V(10,630,1024,90,1,1,-1,1HP,NL)
      CALL RITE2V(10,611,1024,90,1,1,-1,1HA,NL)
      CALL RITE2V(10,592,1024,90,1,1,-1,1HR,NL)
      CALL RITE2V(10,573,1024,90,1,1,-1,1HE,NL)
      CALL RITE2V(10,554,1024,90,1,1,-1,1HN,NL)
      CALL RITE2V(10,535,1024,90,1,1,-1,1HT,NL)
      CALL RITE2V(10,497,1024,90,1,1,-1,1HV,NL)
      CALL RITE2V(10,478,1024,90,1,1,-1,1HI,NL)
      CALL RITE2V(10,459,1024,90,1,1,-1,1HS,NL)
      CALL RITE2V(10,440,1024,90,1,1,-1,1HC,NL)
      CALL RITE2V(10,421,1024,90,1,1,-1,1HC,NL)
      CALL RITE2V(10,402,1024,90,1,1,-1,1HS,NL)
      CALL RITE2V(10,393,1024,90,1,1,-1,1HI,NL)
      CALL RITE2V(10,364,1024,90,1,1,-1,1HT,NL)
      CALL RITE2V(10,345,1024,90,1,1,-1,1HY,NL)
      CALL RITE2V(10,317,1024,90,1,1,-1,1H.,NL)
      CALL RITE2V(10,279,1024,90,1,1,-1,1HC,NL)
      CALL RITE2V(10,260,1024,90,1,1,-1,1HP,NL)
      CALL RITE2V(326,20,1024,90,1,38,-1,38HGAMMA DOT - CORRECTED SHEAR
     1RATE . SEC,NL)
      CALL RITE2V(820,30,1024,90,1,2,-1,2H-1,NL)
C
      CALL LOGFIT(SRC,VISN)
C
C
C  COMPUTE PERCENT MEMORY
      DO 60 I=1,NOF
   60 PERM(I) = (DIA(I)-ODIA)/ODIA*100.
C  CHECK ON PERCENT MEMORY PLOTS
      IFPC = 0
      DO 65 I=1,NOF
      IF(PERM(I).LE.0.) GO TO 65
      IFPC = 1
   65 CONTINUE
      IF(IFPC.EQ.0) GO TO 66
C
C  PLOT - PERCENT MEMORY AGAINST LOG SHEAR RATE
C
C
C   X-AXIS  CORRECTED SHEAR RATE - SRC    Y-AXIS PERCENT MEMORY - PERM
      CALL SETMIV(100,54,54,100)
      CALL SMXYV(1,0)
      CALL GRID1V(3,1000.,1000000.,0.,200.,1.0,20.0,NN,1,II,1,-2,6)
      CALL APLOTV(NOF,SRC,PERM ,1,1,1,1H*,IERR)
      CALL APLOTV(NOF,SRC,PERM,1,1,1,1H*,IERR)
      CALL TITLE(ITEMP,CAP,CLEN,CDIA,ID,IM,IY,SAMPLE)
C  VERTICAL AND HORIZONTAL LABELS
      CALL RITE2V(326,20,1024,90,1,38,-1,38HGAMMA DOT - CORRECTED SHEAR
     1RATE . SEC,NL)
```

```
      CALL RITE2V(820,30,1024,90,1,2,-1,2H-1,NL)                        P1939     185
      CALL RITE2V(10,622,1024,90,1,1,-1,1HP,NL)                         P1939     186
      CALL RITE2V(10,603,1024,90,1,1,-1,1HE,NL)                         P1939     187
      CALL RITE2V(10,584,1024,90,1,1,-1,1HR,NL)                         P1939     188
      CALL RITE2V(10,565,1024,90,1,1,-1,1HC,NL)                         P1939     189
      CALL RITE2V(10,546,1024,90,1,1,-1,1HE,NL)                         P1939     190
      CALL RITE2V(10,527,1024,90,1,1,-1,1HN,NL)                         P1939     191
      CALL RITE2V(10,508,1024,90,1,1,-1,1HT,NL)                         P1939     192
      CALL RITE2V(10,470,1024,90,1,1,-1,1HM,NL)                         P1939     193
      CALL RITE2V(10,451,1024,90,1,1,-1,1HE,NL)                         P1939     194
      CALL RITE2V(10,432,1024,90,1,1,-1,1HM,NL)                         P1939     195
      CALL RITE2V(10,413,1024,90,1,1,-1,1HO,NL)                         P1939     196
      CALL RITE2V(10,394,1024,90,1,1,-1,1HR,NL)                         P1939     197
      CALL RITE2V(10,375,1024,90,1,1,-1,1HY,NL)                         P1939     198
C                                                                       P1939     199
C                                                                       P1939     200
C                                                                       P1939     201
C   OUTPUT                                                              P1939     202
   66 IF(LINE.GE.41) PRINT 5                                            P1939     203
      IF(LINE.GE.41) LINE =9                                            P1939     204
      PRINT 4,SAMPLE,CAP,CLEN,CDIA,ITEMP,ID,IM,IY                       P1939     205
      LINE = LINE+9                                                     P1939     206
    4 FORMAT(1H0/                                                       P1939     207
     1        1H0,1X,*SAMPLE*,2X,5A10,A3/2X,*CAPILLARY*,2X,A7,2X,*L = *, P1939     208
     1F6.4,2X,*D = *,F6.4,2X,*TEMP = *,I3  ,* F*,4X,A2,1X,A3,1X,A2/     P1939     209
     2 1H0,91X,*RABINOWITSCH*,4X,*CORRECTED*,7X,*CORRECTED*/13X,*ORIFICE P1939    210
     3*,4X,*STRAND PERCENT*,11X,*VOLUMETRIC*,7X,*SHEAR*,11X,*SHEAR*,7X, P1939     211
     4*CORRECTION*,8X,*SHEAR*,7X,*VISCOSITY*/5X,*FORCE*2X,*DIAMETER*,   P1939     212
     52X,*DIAMETER*,2X,*MEMORY*,2X,*VOLUME*,9X,*FLOW*8X,*RATE*,10X,     P1939     213
     6 *STRESS*,11X,*FACTOR*,9X,*RATF*,6X,*CENTIPOISE*/)                P1939     214
      DO 70 I=1,NOF                                                     P1939     215
      IF(BVOL.LE.0.) PRINT 7,I,FORCE(I),ODIA,DIA(I),PERM(I),BVOL1(I),Q(I P1939    216
     1),D(I),T(I),CORF,SRC(I),VISN(I)                                   P1939     217
      IF(BVOL.GT.0.) PRINT 7,I,FORCE(I),ODIA,DIA(I),PERM(I),BVOL    ,Q(I P1939    218
     1),D(I),T(I),CORF                                                  P1939     219
     1,SRC(I),VISN(I)                                                   P1939     220
    7 FORMAT(2X,I2,F6.0,3X,F6.3,3X,F6.3,4X,F4.0,2X,F6.4,1X,E13.7,2(2X,  P1939     221
     1 E13.7),2X,E13.7,2(2X,E13.7))                                     P1939     222
      LINE = LINE+1                                                     P1939     223
      IF(LINE.LT.50) GO TO 70                                           P1939     224
      PRINT 5                                                           P1939     225
      PRINT 4,SAMPLE,CAP,CLEN,CDIA,ITEMP,ID,IM,IY                       P1939     226
      LINE =9                                                           P1939     227
   70 CONTINUE                                                          P1939     228
      GO TO 19                                                          P1939     229
  999 GO TO IEOF,(150,1000)                                             P193900     4
  150 IF(IREC.EQ.1)  CALL RECOVE                                        P1939     230
      IF(IREC.EQ.1) CLEN = -1.                                          P1939     231
      IF(IREC.EQ.1)  CALL TITLE(ITEMP,CAP,CLEN,CDIA,ID,IM,IY,SAMPLE)    P1939     232
      REWIND 1                                                          P1939     233
      ASSIGN 1000 TO IEOF                                               P1939     234
      GO TO 19                                                          P1939     235
 1000 CALL EXIT                                                         P1939     236
      END                                                               P1939     237
```

```
      SUBROUTINE LOGFIT(X,Y)
C
C  SUBROUTINE FOR LOG FIT
C
      DIMENSION X(20),Y(20)
      COMMON NOF
      SUMX = 0.0
      SUMLY = 0.0
      SUMX2 = 0.0
      SMXLY = 0.0
      DO 5 K=1,NOF
      IF(X(K).EQ.0.0)XX= 0.0001
      IF(Y(K).EQ.0.0) Y(K) = 0.0001
      ALY = ALOG10(Y(K))
      XX   = ALOG10(X(K))
      SUMX = SUMX+XX
      SUMX2 = SUMX2+XX*XX
      SUMLY = SUMLY+ALY
      SMXLY = SMXLY+XX   *ALY
    5 CONTINUE
      FN = NOF
      DL = (FN*SUMX2)-(SUMX*SUMX)
      IF(DL.EQ.0.0) GO TO 10
      AL = ((SUMLY*SUMX2)-(SMXLY*SUMX))/DL
      BL = ((FN*SMXLY)-(SUMX*SUMLY))/DL
      A = 10.0**AL
      B = BL
      YST = A*X(1)**B
      YLT  = A*X(NOF)**B
      CALL LINEV(NXV(X(1)),NYV(YST),NXV(X(NOF)),NYV(YLT))
      CALL LINEV(NXV(X(1)),NYV(YST),NXV(X(NOF)),NYV(YLT))
      RETURN
   10 PRINT 101
  101 FORMAT(1H0,*COEFFICIENT DET. IS 0. NO SOLUTION*)
      RETURN
      END
```

SUBROUTINE FIT 74/74 CPT=1 FTN 4.2+ REL 12/02/75 03.29.25.

```
      SUBROUTINE FIT(X,Y)                                               P1939   399
C                                                                       P1939   400
C  SUBROUTINE FOR LEAST SQUARES FIT FOR LINEAR PLOTS                    P1939   401
C                                                                       P1939   402
      COMMON NOF                                                        P1939   403
      COMMON /FIT1/ E                                                   P1939   404
      DIMENSION X(20),Y(20)                                             P1939   405
      SUMXY = 0.                                                        P1939   406
      SUMY = 0.                                                         P1939   407
      SUMX = 0.                                                         P1939   408
      SUMX2 = 0.                                                        P1939   409
      DO 10 I=1,NOF                                                     P1939   410
      SUMX = SUMX+X(I)                                                  P1939   411
      SUMX2 = SUMX2+X(I)*X(I)                                           P1939   412
      SUMY = SUMY+Y(I)                                                  P1939   413
   10 SUMXY = X(I)*Y(I)+SUMXY                                           P1939   414
      D = NOF*SUMX2-(SUMX*SUMX)                                         P1939   415
      B = ((NOF*SUMXY)-(SUMX*SUMY))/D                                   P1939   416
      A = ((SUMX2*SUMY)-(SUMX*SUMXY))/D                                 P1939   417
      YST = A+B*X(1)                                                    P1939   418
      YEND = A+B*X(NCF)                                                 P1939   419
      CALL LINEV(NXV(X(1)),NYV(YST),NXV(X(NOF)),NYV(YEND))              P1939   420
      CALL LINEV(NXV(X(1)),NYV(YST),NXV(X(NOF)),NYV(YEND))              P1939   421
       RETURN                                                           P1939   422
      END                                                               P1939   423
```

SUBROUTINE RECOVE   74/74   CPT=1   FTN 4.2+ REL   12/02/75 09.29.20.

```
      SUBROUTINE RECCVE                                                 P1939    293
C                                                                       P1939    294
C                                                                       P1939    295
C   THIS ROUTINE IS USED ONLY FOR CAPILLARY 10-1 AND 250-1 FOR          P1939    296
C    RECOVERABLE SHRESS NUMBER CALUCATIONS.                             P1939    297
C                                                                       P1939    298
      DIMENSION TLOG(20),SRC(20),TLOG1(20),SRC1(20),DUM(20)             P1939    299
      COMMON NNOF,XMAX,XMIN,YMAX,YMIN                                   P1939    300
      EXTERNAL TABL1V                                                   P1939    301
      DO 5 I=1,20                                                       P1939    302
    5 DUM(I) = 0.                                                       P1939    303
      REWIND 1                                                          P1939    304
C   X-AXIS  TLOG        Y-AXIS  SRC                                     P1939    305
C   FIRST CAPILLARY                                                     P1939    306
      READ(1) NOF1,(TLOG(I),I=1,NOF1),XMIN1,XMAX1,CAP1,CLEN1            P1939    307
      READ(1)(SRC(I),I=1,NOF1)                                          P1939    308
C  SECOND CAPILLARY                                                     P1939    309
      READ(1) NOF2,(TLOG1(I),I=1,NOF2),XMIN2,XMAX2,CAP2,CLEN2           P1939    310
      READ(1)  (SRC1(I),I=1,NOF2)                                       P1939    311
      IF(EOF(1).NE.0.0) CALL EXIT                                       P19390C    5
C  MAX AND MIN X FOR PLOTS                                              P1939    312
      XMINS = AMIN1(XMIN1,XMIN2)                                        P1939    313
      XMAXS = AMAX1(XMAX1,XMAX2)                                        P1939    314
C   CONVERT SRC AND SRC1 TC LOG NUMBERS                                 P1939    315
      DO 10 I=1,NOF1                                                    P1939    316
   10 SRC(I) = ALOG10(SRC(I))                                           P1939    317
      DO 15 I=1,NOF2                                                    P1939    318
   15 SRC1(I) = ALOG10(SRC1(I))                                         P1939    319
      NNOF = NOF1                                                       P1939    320
      CALL MAXMIN(SRC,DUM)                                              P1939    321
      XXMIN = XMIN                                                      P1939    322
      XXMAX = XMAX                                                      P1939    323
      NNOF = NOF2                                                       P1939    324
      CALL MAXMIN(DUM,SRC1)                                             P1939    325
C  MAX AND MIN Y FOR PLOTS                                              P1939    326
      YMIN = AMIN1(XXMIN,YMIN)                                          P1939    327
      YMAX = AMAX1(XXMAX,YMAX)                                          P1939    328
      XMIN = XMINS                                                      P1939    329
      XMAX = XMAXS                                                      P1939    330
      LL = 1                                                            P1939    331
      LLL = 1                                                           P1939    332
      IF((XMAX-XMIN).GT.2.) LL = 2                                      P1939    333
      IF((YMAX-YMIN).GT.2.) LLL = 2                                     P1939    334
      XMAX = XMAX+.10000                                                P1939    335
```

```
      YMAX = YMAX+.20000                                                P1939
C                                                                       P1939
C  PRINT OUT OF POINTS THAT ARE PLOTTED.                                P1939
      WRITE(8,1) CAP1,(TLOG(I),I=1,NOF1)                                P1939
      WRITE(8,2) (SRC(I),I=1,NOF1)                                      P1939
      WRITE(8,3) CAP2,(TLOG1(I),I=1,NOF2)                               P1939
      WRITE(8,2) (SRC1(I),I=1,NOF2)                                     P1939
    1 FORMAT(1H0,9X,*RECOVERABLE SHEAR NUMBERS*/10X,*CAPILLARY  *,A7/   P1939
     1 10X,*X = *,3X,(10F8.4))                                          P1939
    2 FORMAT(10X,*Y = *,3X,(10F8.4))                                    P1939
    3 FORMAT(10X,*CAPILLARY  *,A7/10X,*X = *,3X,(10F8.4))               P1939
      CALL SETMIV(100,54,54,100)                                        P1939
      CALL SMXYV(0,0)                                                   P1939
      CALL GRID1V(3,XMIN,XMAX,YMIN,YMAX,.1,.1,1,1,LL,LLL,3,3)           P1939
      CALL CHSIZV(2,2)                                                  P1939
      CALL RITSTV(13,19,TABL1V)                                         P1939
C  HORIZONTAL                                                           P1939
      CALL RITE2V(400,30,1024,90,1,20,-1,20HLOG T - SHEAR STRESS,NL)    P1939
C   VERTICAL                                                            P1939
      CALL RITE2V(10,850,1024,90,1,1,-1,1HG,NL)                         P1939
      CALL RITE2V(10,831,1024,90,1,1,-1,1HA,NL)                         P1939
      CALL RITE2V(10,812,1024,90,1,1,-1,1HP,NL)                         P1939
      CALL RITE2V(10,793,1024,90,1,1,-1,1HM,NL)                         P1939
      CALL RITE2V(10,774,1024,90,1,1,-1,1HA,NL)                         P1939
      CALL RITE2V(10,736,1024,90,1,1,-1,1HD,NL)                         P1939
      CALL RITE2V(10,717,1024,90,1,1,-1,1HC,NL)                         P1939
      CALL RITE2V(10,698,1024,90,1,1,-1,1HT,NL)                         P1939
      CALL RITE2V(10,660,1024,90,1,1,-1,1H.,NL)                         P1939
      CALL RITE2V(10,622,1024,90,1,1,-1,1HC,NL)                         P1939
      CALL RITE2V(10,603,1024,90,1,1,-1,1HC,NL)                         P1939
      CALL RITE2V(10,584,1024,90,1,1,-1,1HR,NL)                         P1939
      CALL RITE2V(10,565,1024,90,1,1,-1,1HR,NL)                         P1939
      CALL RITE2V(10,546,1024,90,1,1,-1,1HE,NL)                         P1939
      CALL RITE2V(10,527,1024,90,1,1,-1,1HC,NL)                         P1939
      CALL RITE2V(10,508,1024,90,1,1,-1,1HT,NL)                         P1939
      CALL RITE2V(10,489,1024,90,1,1,-1,1HE,NL)                         P1939
      CALL RITE2V(10,470,1024,90,1,1,-1,1HD,NL)                         P1939
      CALL RITE2V(10,432,1024,90,1,1,-1,1HS,NL)                         P1939
      CALL RITE2V(10,413,1024,90,1,1,-1,1HH,NL)                         P1939
      CALL RITE2V(10,394,1024,90,1,1,-1,1HE,NL)                         P1939
      CALL RITE2V(10,375,1024,90,1,1,-1,1HA,NL)                         P1939
      CALL RITE2V(10,356,1024,90,1,1,-1,1HR,NL)                         P1939
      CALL RITE2V(10,318,1024,90,1,1,-1,1HR,NL)                         P1939
      CALL RITE2V(10,299,1024,90,1,1,-1,1HA,NL)                         P1939
      CALL RITE2V(10,281,1024,90,1,1,-1,1HT,NL)                         P1939
      CALL RITE2V(10,262,1024,90,1,1,-1,1HE,NL)                         P1939
      CALL RITE2V(54,968,1024,90,1,22,-1,22HCAPILLARY DIAMETER  = ,NL)  P1939
      CALL RITE2V(444,960,1024,90,1,11,-1,11HLENGTHS =   ,NL)           P1939
      ENCODE(6,4,CLEAN)CLEN1                                            P1939
      ENCODE(6,4,CLEAN1)CLEN2                                           P1939
```

```
    4 FORMAT(F6.4)                                              P1939    386
      CALL RITE2V(587,960,1024,90,1,6,1,CLENN,NL)                P1939    387
      CALL RITE2V(691,960,1024,90,1,6,1,CLENN1,NL)               P1939    388
      CALL APLOTV(NOF1,TLOG,SRC,1,1,1,1H*,IERR)                  P1939    389
      CALL APLOTV(NOF2,TLOG1,SRC1,1,1,1,38,IERR)                 P1939    390
      CALL APLOTV(NOF1,TLOG,SRC,1,1,1,1H*,IERR)                  P1939    391
      CALL APLOTV(NOF2,TLOG1,SRC1,1,1,1,38,IERR)                 P1939    392
      NNOF = NOF1                                                P1939    393
      CALL FIT(TLOG,SRC)                                         P1939    394
      NNOF = NOF2                                                P1939    395
      CALL FIT(TLOG1,SRC1)                                       P1939    396
      RETURN                                                     P1939    397
      END                                                        P1939    398
```

```
      SUBROUTINE TITLE(ITEMP,CAP,CLEN,CDIA,ID,IM,IY,SAMPLE)
      DIMENSION SAMPLE(6)
C  TWO LINES OF HEADERS ON PLOTS
      CALL RITE2V( 54,1000,1024,90,1,6,-1,6HSAMPLE,NL)
      CALL RITE2V(159,1000,1024,90,1,53,1,SAMPLE,NL)
      IF(CLEN.LT.0.) GO TO 25
      CALL RITE2V( 54,980,1024,90,1,9,-1,9HCAPILLARY,NL)
      CALL RITE2V(184,980,1024,90,1,7,1,CAP ,NL)
      CALL RITE2V(304,980,1024,90,1,3,-1,3HL =,NL)
      ENCODE(6,21,CLENN)CLEN
   21 FORMAT(F6.4)
      CALL RITE2V(356,980,1024,90,1,6,1,CLENN,NL)
      CALL RITE2V(460,980,1024,90,1,3,-1,3HD =,NL)
      ENCODE(6,21,CDIAA)CDIA
      CALL RITE2V(512,980,1024,90,1,6,1,CDIAA,NL)
   30 CALL RITE2V(616,980,1024,90,1,6,-1,6HTEMP =,NL)
      ENCODE(3,22,ITEMP1)ITEMP
   22 FORMAT(I3)
      CALL RITE2V(727,980,1024,90,1,3,1,ITEMP1,NL)
      CALL RITE2V(759,980,1024,90,1,1,-1,1HF,NL)
      CALL RITE2V(798,980,1024,90,1,2,1,ID,NL)
      CALL RITE2V(837,980,1024,90,1,3,1,IM,NL)
      CALL RITE2V(889,980,1024,90,1,2,1,IY,NL)
      RETURN
   25 CALL RITE2V(54,980,1024,90,1,25,-1,25HRECOVERABLE SHEAR NUMBERS,
     1 NL)
      ENCODE(6,21,CDIAA)CDIA
      CALL RITE2V(340,960,1024,90,1,6,1,CDIAA,NL)
      GO TO 30
      END
```

```
      SUBROUTINE MAXMIN(X,Y)                                  P1939     238
      DIMENSION X(20),Y(20)                                   P1939     239
      COMMON NOF,XMAX,XMIN,YMAX,YMIN                          P1939     240
C  MAX AND MIN VALUES FOR FLCTS                               P1939     241
      XMAX = -9999.                                           P1939     242
      XMIN = 9999.                                            P1939     243
      YMAX = -9999.                                           P1939     244
      YMIN = 9999.                                            P1939     245
      DO 10 I=1,NOF                                           P1939     246
      IF(X(I).GT.XMAX) XMAX = X(I)                            P1939     247
      IF(X(I).LT.XMIN) XMIN = X(I)                            P1939     248
      IF(Y(I).GT.YMAX) YMAX = Y(I)                            P1939     249
      IF(Y(I).LT.YMIN) YMIN = Y(I)                            P1939     250
   10 CONTINUE                                                P1939     251
C  RESET MAX AND MIN LIMITS FOR PLOTS                         P1939     252
      MAX = XMAX+.9                                           P1939     253
      XMAX = MAX                                              P1939     254
      MAX = YMAX+.9                                           P1939     255
      YMAX = MAX                                              P1939     256
      MIN  = XMIN-.5                                          P1939     257
      XMIN = MIN                                              P1939     258
      MIN  = YMIN-.5                                          P1939     259
      YMIN = MIN                                              P1939     260
      RETURN                                                  P1939     261
      END                                                     P1939     262
```

```
          PROGRAM P1939       74/74    CPT=1                               FTN 4.2+ REL        12/02/75  09.28.59.

CARD NR. SEVERITY  DETAILS    DIAGNOSIS OF PROBLEM

    29     I        24 CD 29 FIELD WIDTH OF A CONVERSION DESCRIPTOR SHOULD BE AS LARGE AS THE MINIMUM
                             SPECIFIED FOR THAT DESCRIPTOR.
```

SYMBOLS

L/D	length to diameter of capillary
ASTM	American Society for Testing and Materials
sec^{-1}	reciprocal second
F	force in pounds or dynes
Na	absolute viscosity, poise
R	barrel radius, cm
r	capillary radius, cm
L	capillary length, cm
Q	extrusion rate, cm^3/sec
$\dot{\gamma}_{\dot{\omega}}$	shear rate, sec^{-1} (corrected)
cp	centipoise
b	slope of flow curve
P	pressure difference ($dynes/cm^2$)
T	shear stress ($dynes/cm^2$)
S_r	recoverable shear number
D	diameter strand or capillary diameter

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